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Volume 10

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ERCB and CONCORD ENVIRONMENTAL

Summary

ERCB Field Measurement Program and Concord Environmental Corporation GASCON2 and Risk Approach

October 1990

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ERCB Field Measurement Program and Concord Environmental Corporation GASCON2 and Risk Approach

Summary of the ERCB Field Measurement Program and Concord Environmental Corporation GASCON2 and Risk Approach

Volume 10

October 1990

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Organization of Document

This document is a compilation of the summaries from each of the other Volumes, with the exception of Volumes 8 and 9. A Background section has also been included to give the reader a more complete picture of the project.

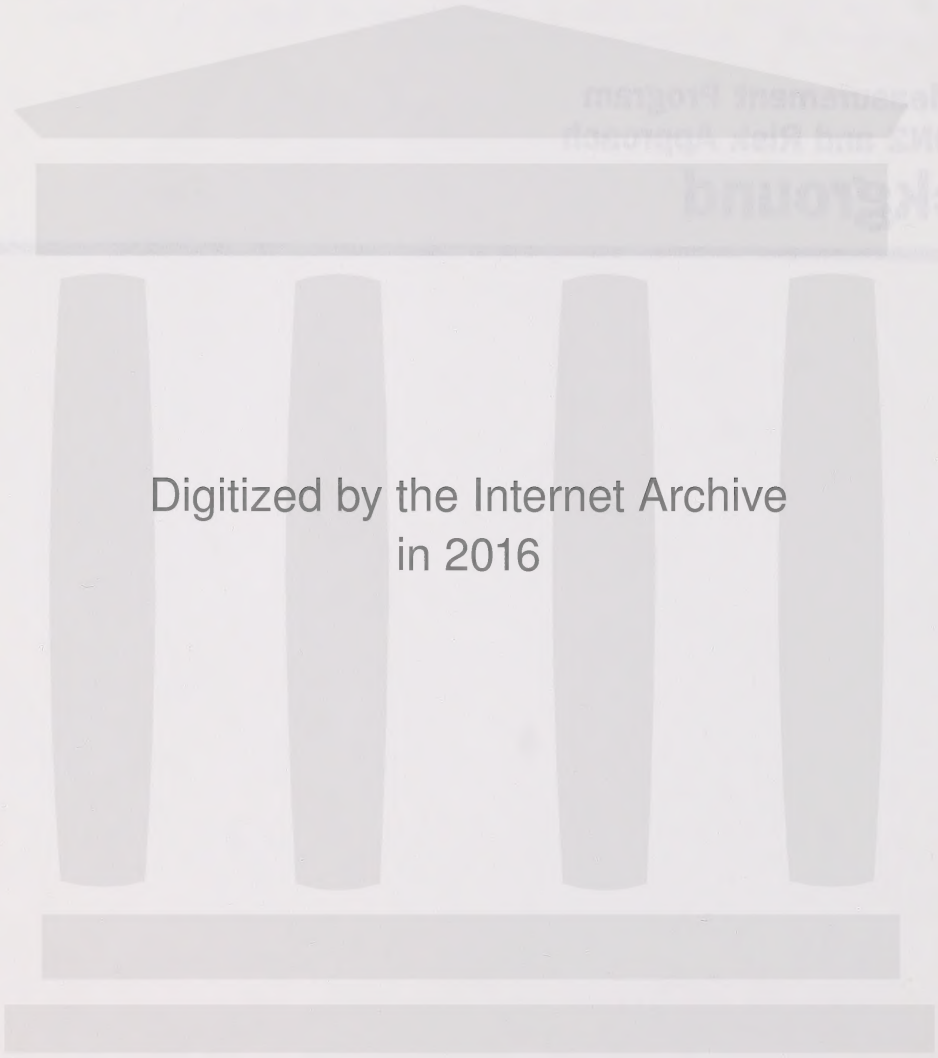
For Volumes 1, 4, 5 and 6 the acknowledgements and executive summaries are included in this document. For Volumes 2 and 3 the table of contents and sample data pages are presented. For Volume 7 the table of contents, list of figures, list of tables, acknowledgements and sample data pages are presented.

ERCB Report 90-B

ERCB

Field Measurement Program GASCON2 and Risk Approach
Background

October 1990



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BACKGROUND

FIELD MEASUREMENT PROGRAM

GASCON2 AND AN APPROACH TO RISK CALCULATION

Why were the studies undertaken?

For many years the Energy Resources Conservation Board (ERCB) has strongly enforced safety policies regarding the handling of sour gas resources in the province of Alberta. Emergency planning zones and appropriate setback distances, between residents and sour gas facilities, have been established to ensure that risks are minimized. Typically, sour gas facilities include wells, pipelines and processing plants. During the historical period in which sour gas has been produced, many improvements have been made to the methods for handling this valuable but toxic material.

While these improvements have reduced the risks to both workers and the public, the concerns have continued to increase, particularly as a result of the 1982 Lodgepole well blowout, but also in response to an increasing number of applications for sour gas developments near populated areas. In 1986, these increasing public concerns prompted the ERCB to commission Concord Scientific Corporation (now Concord Environmental Corporation) to independently develop sour gas hazard and risk assessment models (known as GASCON and GASRISK respectively). A Scientific Advisory Board (SAB) was then established to oversee the work.

What were GASCON and GASRISK?

The GASCON (gas concentration) and GASRISK (risk) computer models are referenced in many earlier documents. This backgrounder provides a brief explanation of what these two computer models originally were designed to do (see Chronology of Events) and how and why the two models have been combined into one.

The GASCON computer model was designed to simulate a well blowout or pipeline rupture involving sour gas. GASCON predicted downwind gas concentrations for both ignited and non-ignited gas plumes. The GASCON computer model was developed using experiences gained from several earlier models plus new information which the ERCB, Concord Environmental and others had developed to predict the behaviour of sour gas under various conditions.

Originally, GASRISK was a computer model designed to calculate the likelihood of a sour gas event actually happening, and the consequences of such an event should one occur. Once an uncontrolled release of gas had been described for a specific case (e.g. the size of the pipeline involved, the type of gas, the various weather conditions, the direction of release and the type of failure), GASRISK would then estimate the likelihood of the release actually happening and the likelihood that exposure to the gas cloud could result in fatalities.

Why did the studies expand to include field testing?

GASCON was a more rigorous model than those previously used and could predict both hydrogen sulphide (H_2S) and sulphur dioxide (SO_2) concentrations under various scenarios. However, the highest concentrations predicted for H_2S releases were under calm conditions, where the wind speeds were less than 1 m/s (4 km/h). The draft GASCON model results were released in June 1987, followed by a recommendation from the public to evaluate the model with actual field testing, prior to completion of both the GASCON and GASRISK work. All sectors, including the public, government and industry, supported this recommendation.

The ERCB established Management and Technical Committees in late 1987 to provide direction and technical support for a field testing program. Representatives on those committees were drawn from the industry and the public. Prior to the field testing, the Technical Committee (TC) reviewed the dispersion model results, and confirmed that low turbulence atmospheric conditions warranted the most attention when predicting the behaviour of an accidental release of H_2S.

In June 1988, after the Technical Committee had determined the scope of the study, tender invitations were requested from across Canada and the United States. In August 1988, a contract for key aspects of the program was awarded to Concord Environmental Corporation, with Promet Environmental Group and Indaco Air Quality Services acting as subcontractors. The ERCB managed the overall program.

What was included in the Field Measurement Program?

The Field Measurement Program was conducted on reasonably flat farm land approximately 20 km northeast of the city of Calgary. The tracer release and sampling occurred during the months of October, November and December 1988. The meteorological station commenced operation in October 1988 and continued to operate until a 12-month set of data had been collected. The Technical Committee designed a program consisting of two parts, a tracer and a meteorological study:

Tracer Study

The tracer study was the focus for an intensive 3-month period, when a harmless tracer gas (SF_6) was released under low wind speed conditions. Concentrations were measured at several downwind locations to determine the amount of dilution in the tracer gas plume. During the tracer releases, concurrent meteorological data were obtained to aid in the interpretation of the tracer gas results.

Meteorological Study

The meteorological study involved the collection of atmospheric turbulence and wind profile data to obtain meteorological information on the frequency and behaviour of low turbulence atmospheric conditions.

Why did GASCON/GASRISK become GASCON2 and a Risk Approach?

Data reduction and analysis of the field tests began in January 1989 and continued until August 1990. A review of the field analysis results during that time indicated that certain GASCON assumptions would have to be changed and these changes were incorporated.

As the work proceeded, it became apparent that the consequence aspect of the GASRISK model tied in more closely with the GASCON computer modelling, whereas the fault tree or likelihood component did not lend itself to the same type of computer modelling. What was developing instead was an approach for calculating the risk, rather than fully modelling it. For that reason, the scientists came to the conclusion that it would be advisable to move the consequence portion of the GASRISK model into the downwind concentration model (GASCON), thus producing a single computer-based program.

It was important to give the new model a name and, since it was now a **con**centration and **con**sequence model, the acronym became GASCON2. Although the earlier documents released referred to GASCON and GASRISK, the material being released now refers only to GASCON2 as a computer model. The portion of the project defining a risk approach, such as failure statistics and fault tree analysis, remained a separate study.

Was the new GASCON2 evaluated against the field data?

The answer is yes. However, GASCON2 has the ability to handle many complex scenarios and was developed in a modular fashion to incorporate the appropriate physics. The Field Measurement Program was only designed to deal with the passive dispersion of a tracer gas; therefore, the model evaluation was limited to the passive dispersion module of GASCON2. A simple Gaussian model was also evaluated and used as a benchmark for comparison purposes.

What has the research cost?

The project cost to develop the model and carry out the field tests was in excess of 1 million dollars. These funds were provided by the ERCB and the oil and gas industry, through the Canadian Petroleum Association, Independent Petroleum Association of Canada and Small Explorers and Producers Association of Canada and the two major electric utilities in the province. As well, significant contributions of expert personnel and loans of equipment were made by the public, industry and Alberta Environment.

How was the research managed?

Throughout the 4-year research effort, the ERCB has served as overall project manager. To assist in carrying out the work, and especially to ensure that all scientific work would be subject to on-going peer evaluation, the ERCB:

- Ensured the on-going peer review of all work and results, by establishing an independent Scientific Advisory Board (SAB), each member having scientific expertise in the subject of focus. The SAB was assigned the specific task of reviewing and commenting on the work of Concord Environmental. The SAB provided a written analysis, in 1987, on GASCON when it was first released and provided a second assessment when the work on GASCON2, GASCON2 Evaluation, and the Risk Approach was finally concluded.

  Scientific Advisory Board membership includes:

David Wilson, Chairman	University of Alberta
Randy Angle	Alberta Environment
Bob Rogers	TOXCON
Ross Purvis	ERCB

- The Field Measurement Program was directed by the Management Committee made up of industry and public representation. The committee consisted of:

F. J. Mink, Chairman	ERCB
E. A. McMaster	Industry Representative Shell Canada
E. C. Brown	Public Representative City of Calgary

- Assisted with the work of the Field Measurement Program, by also establishing a Technical Committee (TC). This expert team assisted in the design of the Field Measurement research and provided feedback during the course of the testing program.

  Technical Committee membership includes:

Ed Fox, Chairman	ERCB
Lynda Holizki	ERCB
Keith Hage	Public representative
David Wilson	University of Alberta
Randy Angle	Alberta Environment
Sven Djurfors	Syncrude Canada
Hugh Brown	Esso Resources
Jim Swiss/Gary Webster	Canadian Petroleum Association

- Ms. Lynda Holizki, P. Eng, acted as ERCB's overall project coordinator for the total research effort.

The Scientific Advisory Board provided a commentary on the GASCON2 report, the model evaluation and the risk approach.

Did the public and industry get their money's worth?

One way of answering the question might be to see if we accomplished our original objectives. A 10-volume series of reports has been prepared summarizing the results of the Field Measurement Program and model development.

At the outset of this project the public questioned what could happen as a result of a sour gas well and pipeline failure. Specifically, they wanted to know how bad it could get and how many fatalities there might be. The public also suggested we look at realistic cases. The industry was interested in the same information, except that it had a great deal of actual experience and it encouraged the ERCB to look at the historic data to ensure that the resulting model predictions were put into real-life perspective by considering actual field experience.

In summary, even with changes to GASCON and GASRISK, there were cases that could be modelled that resulted in reasonably large concentrations downwind, but not as high as was originally anticipated. Field tests substantiated the new model results; and confirmed that, if the worst-case failure happens, there can be hazards, the extent of which would depend on the volume of gas released and the population density. In all of the modelling, only the very large well or pipeline cases (e.g. Lodgepole size) were predicted to result in fatalities, when the incident occurred near a populated area. There were some situations where, if the individual was very close to the failure, there were predicted fatalities. Generally, estimates of public risk were very low.

The historic information also helps put things into perspective. These large modelled cases rarely happen and, in fact, for some of the cases where potential problems might be expected, there is an opportunity to enhance the design of the system to try to mitigate those risks. One thing that can be done is to have a procedure in place to ignite the well in the event of a blowout.

The great success of the project is that a significant field data set now is available for the first time to evaluate other models; and there now are tools with which to do further evaluation and sensitivity on important issues like mitigation. The true test in the value of the modelling and Field Measurement Program efforts will be in increasing the level of confidence in decisions concerning the new sour gas facilities in areas which are populated.

Can anyone get the data, models and reports?

The working level data, the models and a set of 10 documentary volumes will be available for anyone wishing to obtain a copy. The ERCB's library as well as libraries across Canada will be supplied with copies of the reports. There will be some cost associated with the data, models and reports. While there is a cost, it is not the intention of the ERCB to prohibit a member of the public from obtaining a copy, and it would supply copies at a nominal charge. Industry contributors will also receive sufficient copies before being charged a fee.

Additionally, the ERCB has tendered the field measurement equipment and is prepared to sell the four sonic anemometers and the one remaining continuous analyser.

AVAILABLE REPORTS

What reports are being released and what do they contain?

There are 9 volumes in the package of material being released on 23 October 1990 with the remaining volume to follow in a few weeks. That will be Volume 9, the Scientific Advisory Board Commentary. These reports are under a general ERCB category, ERCB Report 90-B and also bear the numbers and titles shown here:

ERCB Volume 1	**Field Measurement Program** Atmospheric Dispersion Tracer Study Under Stable Conditions and Meteorological Study (500 pages)
ERCB Volume 2	**Field Measurement Program** Appendices to Volume 1 - Appendix A (600 pages)
ERCB Volume 3	**Field Measurement Program** Appendices to Volume 1 - Appendices B through D (400 pages)
ERCB Volume 4	**Field Measurement Program** GASCON2 Evaluation (250 pages)
Concord Volume 5	**GASCON2** A Model to Estimate Ground Level H_2S and SO_2 Concentrations and Consequences from Uncontrolled Sour Gas Releases (300 pages)
Concord Volume 6	**Risk Approach** An Approach for Estimating Risk to Public Safety from Uncontrolled Sour Gas Releases (150 pages)
ERCB Volume 7	**Risk Approach** ERCB Supplemental Appendices to Volumes 5 and 6 (200 pages)
ERCB and Concord Volume 8	**GASCON2 User Guide** (30 pages)
ERCB and Concord Volume 10	**SUMMARY** of the ERCB Field Measurement Program and Concord Environmental Corporation GASCON2 and Risk Approach (150 pages)
ERCB	**Background**

FINDINGS

A brief explanation of each of the reports being released appears below:

Volume 1 - Field Measurement Program. The primary objective was to investigate the behaviour of H_2S gas at low wind speeds and under calm atmospheric conditions. This was considered the worst-case scenario for an uncontrolled release of sour gas, because under these conditions negligible mixing with the surrounding uncontaminated air mass was expected and people exposed to the gas could be in danger.

The Field Measurement Program produced four important findings in this regard:

1. It confirmed a number of mathematical relationships which formed the basis for describing the turbulence and subsequent plume behaviour in the atmosphere.

2. The largest ambient concentrations are associated with ground releases which do not have any accompanying plume rise.

3. Low wind speeds do not occur as frequently as expected, **nor** do they last for as long as expected. In the Crossfield/Calgary area, stable conditions with low wind speeds, less than two m/s, occur less than 10% of the time and they usually last 1 hour or less and only rarely do they last for 3 hours or more. This information can now be used to look at the overall risk or likelihood of these atmospheric conditions occurring.

4. The smallest plume spreads and the highest concentrations did not occur at the lowest wind speeds as expected. They were thought to occur at wind speeds less than 1 m/s, but occurred - on average - at wind speeds around 3 to 4 m/s.

Volumes 2 and 3 - Field Measurement Program contain appendices to Volume 1. Volume 2 has the traverse data for the 846 traverses. Volume 3 has the stationary data for the 5271 3-minute periods, along with other data on the release source and meteorology. A concentration graph is provided for each traverse or stationary period, along with accompanying statistics for each plume.

Volume 4 - Field Measurement Program, GASCON2 Evaluation contains the results of the Field Measurement Program as they were applied to GASCON. These results indicate:

1. The GASCON2 passive dispersion module can predict worst-case concentrations that might occur during a toxic release with reasonable accuracy (factor of two). In the world of dispersion modelling, GASCON's performance was considered good.

2. The GASCON2 model met the United States EPA protocol "first test" for establishing the best models for regulatory purposes. If a model does not pass the "first test", then EPA would not allow this model to be used.

3. Generally GASCON2 overpredicted at high concentrations, however, it was found that the GASCON2 model sometimes assumed neutral atmospheric conditions when stable conditions were observed. This led to an underprediction of results for those cases. GASCON2 appeared to be doing a good job of tracking the field observations and performed well at the high concentration end. It is not clear whether this model discrepancy is related to the model formulations or field input data.

4. The confidence in GASCON2 was increased substantially with the field testing and the scientists evaluating GASCON2 recommended that the model could be used without further enhancements. In the future when research moves the science forward and modifications are recommended, these changes should be incorporated.

Volume 5 - the GASCON2 report provides estimates of concentrations downwind for many typical well and pipeline accidental releases. The model has the flexibility to address a wide range of well blowout and pipeline rupture scenarios for different meteorological conditions. The flexibility and capability allows GASCON2 to be used as a planning tool when sour gas production alternatives are being evaluated. The results indicate:

1. That the highest concentrations of H_2S were still predicted during near calm conditions, at wind speeds less than 1 m/s. As was seen in the Field Measurement Program, these may not be real world "worst-case" conditions.

2. That horizontal ground releases were potentially the most dangerous type. In these cases, the plume could be directed towards populated areas rather than coming out more like a vertical jet rising into the higher layers in the atmosphere.

3. That GASCON2 model predictions compared favourably to the Lodgepole monitored gas concentration readings. If anything, there was some overprediction by GASCON2.

4. The predicted concentrations of sulphur dioxide (SO_2) were never in the lethal exposure range thus no fatalities were predicted. The largest concentration values occurred at higher wind speeds and unstable conditions.

5. That for any such accidental release, the model predicts at what location fatalities are likely to occur. Since hydrogen sulphide (H_2S) toxic load is dependent on the gas concentration and duration of exposure, the distances where conditions are lethal will vary. Fatalities will also vary depending on the number of people exposed. Generally, the highest number of fatalities is expected under the calm weather conditions.

Volume 6 - the **Risk Approach** report provides the approach to calculate the individual and societal risk given the probability of lethality. Examples for certain well and pipeline cases presented in GASCON2 are included.

Volume 7 - the **Risk Approach Appendices** contains historic information from 1975 to 1989 on well blowouts and pipeline ruptures in Alberta. This is the first time this extensive information has been provided in both the sweet and sour gas categories. This is also the first time toxic load information for H_2S (combining length of exposure time and gas concentration) has been presented in summary form.

For Volumes 6 and 7, results indicate:

1. The likelihood of a sour well blowout or pipeline rupture is extremely low, especially when considering the large numbers of wells and pipelines in the province. Historically, during the 13 year period (1976 - 1988), there were only 5 sour well blowouts out of 11000 sour wells drilled; with 14 blowouts out of 63000 well years of service for either producing, suspended or abandoned. Pipeline statistics show only 28 ruptures over 47500 km of sour gas pipeline.

2. Even though the frequency of a sour well blowout is similar for the drilling, producing and suspended well cases, the likelihood of a blowout is highest during the servicing stage rather than drilling. These are the times when a producing or suspended well could have flow up the open hole (casing), such as during a workover with the tubing pulled; but such operations occur, on average, for only a 2-week period every 2 to 4 years. Normally, a producing or suspended well would have less potential for flow because it would have tubing in the hole.

   Situations that result in flow up the casing (drilling or servicing) are always manned by someone who has the authority to ignite the well. Therefore, any well situation expected to have high flow potential can be managed so that the H_2S release will last no longer than 30 to 60 minutes.

3. The percentage of sour wells being drilled is on the increase, likely due to the fact that the industry is exploring the deeper gas formations of the foothills region in the province.

4. The frequency of pipeline ruptures is higher for buried pipelines than for pipeline surface equipment. However, a rupture at a surface facility may end up being a horizontal rather than vertical release. Most buried pipes would have at least some angle of deflection so that the plume would likely end up being vertical. Horizontal releases were predicted to give the largest downwind concentrations.

   So, while it may appear that it would be better to add valves to a lengthy pipeline, this competing effect is important. In fact, the size of the pipeline and the volume that could be released would also have some bearing on the results. The answer to "whether or not more valves should be added" will depend on all of these issues. The new risk approach provides a tool to answer this on a case-by-case basis.

5. From experience, the "worst cases" that can be modelled by GASCON2 rarely happen. Well blowouts and pipeline ruptures have historically been vertical more frequently than horizontal. Only 3 out of 22 blowouts were flowing up the casing, with 6 of those

being horizontal releases. Additionally, pipeline ruptures have not been the type that have a full cross-section opening of the pipe. Historically evidence shows that most openings have been less than 1 to 5% of the actual pipe diameter.

6. Leaks do occur around ten times more often than ruptures. However, because the volumes released are small, the likelihood of fatality is low unless someone is close to the facility. There may be cases where the leak size will be large enough to create a hazard, but too small to trigger a valve closure. These cases were simulated using GASCON2 and were found only to be hazardous near the source.

7. It appears that the age of the facility was not a significant factor contributing to the historical incidence of well blowouts or pipeline ruptures. The incidents tended to occur either in the first few years of operation or at no set time after that. Inspection requirements and good engineering operating practice likely contribute to improving this record.

8. A significant feature of the risk approach is the ability to identify areas where mitigative measures could substantially reduce the risk to public safety. For instance, if horizontal deflectors could be used around wells or pipeline surface facilities, the risk would be reduced. This measure may be considered for potentially high volume releases near populated areas. Whether or not this would be a practical solution needs further consideration. Other mitigative measures such as deeper pipeline burial and ignition were also identified.

   The key is that the risk approach has the capability to investigate these proposed measures in a qualitative manner. A facility risk model would be able to handle these issues in an even more rigorous manner and may be developed later.

9. The probit approach was incorporated in the GASCON2 model. It takes into account the fact that sensitive individuals may not require the same dose of H_2S as stronger individuals, to become fatalities. The supporting documentation on the toxic load is provided, for the first time on record.

Volume 8 is the **GASCON2 User Guide** to the model. Examples are provided to make the guide more user friendly, and even though the model is on an IBM Personal Computer or compatible, it will require some atmospheric science expertise to run.

Volume 9 is the **Scientific Advisory Board's Commentary** on Volumes 4, 5 and 6.

Volume 10 - the **SUMMARY** pulls together the individual summaries of certain key volumes. It contains a brief summary of each of the reports and selected highlights. This will be of use for general readers and will act as a guide for people who want a brief introduction to the research.

CHRONOLOGY OF EVENTS

ERCB - FIELD MEASUREMENT PROGRAM AND CONCORD ENVIRONMENTAL CORPORATION - GASCON2 AND RISK APPROACH

1984 CANADIAN OCCIDENTAL PETROLEUM COMPANY APPLIED TO THE ERCB TO DRILL SOUR GAS WELLS IN NORTHEAST CALGARY

1985 AT PUBLIC REQUEST, A **SOUR GAS TASK FORCE** MADE UP OF REPRESENTATIVES OF PUBLIC, INDUSTRY AND LOCAL AND PROVINCIAL GOVERNMENTS WAS FORMED.

AT CITIZEN REQUEST, THE CITY OF CALGARY SPONSORED **SAGE COMMUNITY STUDY**, FOLLOWED BY REPORT TO LOCAL RESIDENTS.

SAGE REPORT **RECOMMENDED** INDEPENDENT REVIEW AND RESEARCH INTO **THE REASONABLE WORST CASE ACCIDENTAL RELEASE**.

1986 **CONCORD SCIENTIFIC CORPORATION HIRED** BY THE ERCB TO CARRY OUT THE NECESSARY RESEARCH. CONCORD'S WORK TAKES SHAPE UNDER COMPUTER MODELS DUBBED "GASCON" AND "GASRISK".

SCIENTIFIC ADVISORY BOARD APPOINTED BY ERCB TO OVERSEE AND REVIEW TECHNICAL WORK.

1987 **FIRST PUBLIC RELEASE OF "GASCON"**.

REVIEW OF "GASCON" AND RECOMMENDATION THAT WORST-CASE ESTIMATES BE EVALUATED THROUGH ACTUAL MEASUREMENT ACTIVITIES IN THE FIELD UNDER CALM CONDITIONS.

1988 MANAGEMENT AND TECHNICAL COMMITTEES APPOINTED BY THE ERCB TO DESIGN AND PROVIDE TECHNICAL SUPPORT ON FIELD WORK.

1988/89 **FIELD MEASUREMENT PROGRAM CONDUCTED** UNDER ERCB MANAGEMENT, NORTHEAST OF CALGARY, NEAR THE HAMLET OF KATHYRN.

1989/90 **FIELD MEASUREMENT RESULTS ANALYSED** AND APPLIED TO "GASCON" COMPUTER MODEL.

March 1990 RESEARCH **RESULTS REQUESTED** BY COMPANIES AND INTERVENERS INVOLVED IN THE **CAROLINE** GAS FIELD HEARING.

April 1990 **ERCB DECIDED TO PRE-RELEASE** THE FIELD MEASUREMENT PROGRAM RESULTS WITH ADDITIONAL SCIENTIFIC REVIEW TO FOLLOW.

May 1990 MODEL CHANGES STARTED - **GASCON/GASRISK BECOME GASCON2 AND RISK APPROACH.**

ERCB D 90-8 August 1990 HUSKY AND SHELL APPLIED GASCON/GASRISK TO THEIR CAROLINE APPLICATIONS. GASCON/GASRISK RESULTS WERE LESS CONSERVATIVE THAN THOSE ORIGINALLY SUBMITTED BY SHELL AND HUSKY. DECISION REPORT ERCB D#90-8 APPROVED SHELL PROPOSAL - COMMENT WAS MADE ON APPLICABILITY OF MODELS AND RISK.

Oct 1990 **FINAL PUBLIC RELEASE** OF ALL TEN VOLUMES.

1990/91 PLANS INCLUDE PRESENTATIONS FOR INDUSTRY, OTHERS IN THE SCIENTIFIC COMMUNITY AND A SCIENTIFIC WORKSHOP FOR INDUSTRY AND PUBLIC.

ERCB Report 90-B
Volume 1

ERCB

Field Measurement Program

Atmospheric Dispersion Tracer Study Under Stable Conditions and Meteorological Study

October 1990

Acknowledgements

The ERCB managed the Field Measurement Program which was a joint effort receiving significant financial, equipment and manpower support from government and industry. These contributions are identified specifically in Section 1.2.2. Photos of the landowners, contributions, management and technical committees and communication efforts are shown on the following page. Additionally, there were other contributions made to the program which made it a success and the ERCB would like to express its appreciation for those special efforts to:

- The landowners, Harold and Marion Randall, who offered their property, generous support and a warm welcome to all project staff. They hosted a media tour and a wind-up barbecue. Their neighbourly attitude proved to be a valuable asset to the smooth sailing of the program.

- The local people from the Kathyrn area who provided enthusiasm and support:

  Judith Barry (sign/poster painting and newsletter distribution)
  Ernie Harrison (monitoring truck driver)
  Max Nichols (monitoring truck driver)
  Stewart Randall (monitoring truck driver)
  Ian Willdig (monitoring truck driver)
  Warren Wise (mechanic)

- The Management Committee members who offered encouragement and kept the program on track by overseeing all aspects:

  Frank Mink
  Ted Brown
  Ed McMaster

- The Technical Committee members, who defined the scope and provided feedback during the course of the program, are gratefully acknowledged. There were many technical meetings as well as lengthy phone calls and many hours spent on the review of data as it was generated. In particular, Randy Angle, Sven Djurfors, Keith Hage and David Wilson spent many hours on data review. Without this input, progress would have been difficult. The expertise among the members provided the necessary direction to the project:

  Randy Angle
  Hugh Brown
  Sven Djurfors
  Ed Fox
  Keith Hage
  Lynda Holizki
  Jim Swiss
  David Wilson

- The Program Co-ordinator, Lynda Holizki of the ERCB, provided the link to all aspects of the project. She was the Senior Environmental Engineer responsible for technical direction, data analysis, report writing, budget reviews, technical meetings and some aspects of public communication. Lynda was involved in authoring and reviewing all four volumes of the Field Measurement Program.

- The Field Project Manager, Vic Bohme, who provided strong leadership and motivation and provided the needed encouragement to operate from dusk to dawn.
- The Principal Investigator, Mervyn Davies of Concord Environmental Corporation, whose expertise in field work, meteorology and computer applications made him a key individual during the design and implementation of the field program and during the analyses and interpretation of the data. Mervyn was the primary author of Volume 1.
- Touche Howard of Indaco Air Quality Services was responsible for many technical aspects of the tracer analysis. He was also the primary author of the model evaluation report, Volume 4.
- The ERCB Communications Department, in particular Jack Bales and George Kupfer, who spent time with the public, the media and newsletter production. They developed the communication plans throughout the program.
- The project staff who worked many more hours than were originally anticipated. There were a total of 26 people whom we mention here, however; other staff in these organizations assisted:

ERCB Technical Staff	Paul Angrave	Concord Environmental Corporation Staff	Mike Brennand
	Ken Bahadur		Mervyn Davies
	Jim Davis		Ann Jamieson
	Arnold Dick		Judy Smith
	Ian Dowsett		
	Brian Fleck	Indaco	Alex Guenther
	Lynda Holizki		Touche Howard
	Joseph Mathews		Brian Lamb
	Ross Purvis		
	Brad Simm	Promet	David Chadder
	Stephen Skarstol		Steward Bonner
	John Sutherland		Bill Murray
	Dean Webster		Craig Schneider
	Richard Wright		
		Others	Roberta Hicklin

- Peter Slawson, a special technical adviser, provided advice on atmospheric dispersion field programs when the program was in the conceptual design stage.
- The support staff from the ERCB in purchasing, drafting, printing, core research storage, shipping and data processing who were a big help. In particular, Paul Angrave who assisted at the meteorological station and took numerous documentary photos, most of which appear in the text of this report.
- The Environment Protection Department staff who have helped with both moral and technical support. Richard Wright was responsible for the production and technical editing of the report and he was assisted by Ann Elahee, Susan Foulds and Janet Shortridge, who typed most of this document on the personal computer.

The combined efforts and support of the above personnel made this ambitious effort a reality.

Harold Randall	Vic Bohme	George Kupfer	Lynda Holizki	Marion Randall

The Landowners with Members of the Field Measurement Program Project Team.

RESEARCH PROJECT FIELD OFFICE
ERCB
Energy Resources Conservation Board
AIR MONITORING VEHICLES WILL OPERATE SOUTH OF HERE FROM SEPT-DEC 1995
PLEASE DO NOT DISTURB THE RESEARCHERS DURING THEIR WORK
INFORMATION 297-3722

Contributions such as the Field Offices and Signs made the Project Possible.

Management Committee

(T. Brown, F. Mink (Chairman), E. McMaster)

Technical Committee and Project Staff

Technical Committee seated: E. Fox, V. Bohme, D. Wilson, K. Hage, S. Djurfors, R. Angle, H. Brown, (L. Holizki standing)
Project staff standing: T. Howard, J. Sutherland, R. Purvis, I. Dowsett, J. Davis, R. Wright, L. Holizki, D. Webster, M. Davies, M. Brennand, S. Skarstol. Missing: J. Swiss, K. Bahadur, P. Angrave, B. Fleck, A. Dick.

Field Measurement Program Summary

Introduction

The ERCB has strongly enforced policies regarding sour gas emergency planning zones and appropriate setback distances between sour gas facilities and residents, which include wells, pipelines and processing plants. Over the many years of sour gas production, there have been improvements in the handling of sour gas, qualitatively reducing the risk to workers and members of the public. However, public concern regarding sour gas has grown, particularly because of the 1982 Lodgepole sour gas well blowout and increased sour gas development near populated areas.

These public concerns prompted the ERCB to commission Concord Scientific Corporation (now Concord Environmental Corporation) to independently develop hazard and risk assessment models (GASCON and GASRISK respectively) in 1986. A Scientific Advisory Board was established to oversee the work.

The draft GASCON model results were released in June 1987 and were followed by a recommendation to do a model evaluation with actual field testing, prior to completion of both the GASCON and GASRISK work. All sectors including the public, government and industry supported the recommendation for such a field program.

The ERCB assumed primary responsibility for management of the Field Measurement Program and obtained co-operation and support from the public, government and industry. The significant funding in the order of $500 000 came from industry with additional financing, equipment and manpower support from government and the ERCB. A Management Committee and Technical Committee, both chaired by the ERCB, were established in late 1987 to provide direction and technical support. Details of the program's contributions and administration are contained in Section 1.2, Volume 1. More specifically, the Technical Committee was appointed to determine the technical scope and design of the program and provide feedback on results as they were generated.

Prior to the field testing, the Technical Committee reviewed the GASCON and simple Gaussian model results, and confirmed that low turbulence atmospheric conditions warranted the most attention when predicting the behaviour of an accidental release of hydrogen sulphide. GASCON was a more rigorous model than the simple Gaussian model and could predict both hydrogen sulphide and sulphur dioxide concentrations under various scenarios. However, the highest hydrogen sulphide concentrations predicted were for stable conditions when the wind speeds were less than 1 m/s.

In June 1988, once the Technical Committee had determined the scope, tender invitations were requested. In August 1988, a contract for key aspects of the program was awarded to Concord Environmental Corporation with Promet Environmental Group and Indaco Air Quality Services acting as subconsultants. A number of ERCB staff were also involved in the field work.

The Field Measurement Program co-ordinator was Lynda Holizki (ERCB), who was assisted by:

- Vic Bohme, who acted as field program manager,
- Mervyn Davies (Concord) and Touche Howard (Indaco), who acted as primary technical consultants,
- George Kupfer and Jack Bales (ERCB), who acted as communication co-ordinators, and
- the Technical Committee and many ERCB staff.

The Field Measurement Program started in September 1988 with considerable support from the public, industry and government. Data analysis started in January 1989 and continued until October 1990. All results were documented and are contained in Volumes 1, 2 and 3. A review of the field analysis results indicated that certain GASCON assumptions should be changed. These changes were incorporated into a new model that had integrated the GASCON and GASRISK models. The new model was called GASCON2 as it incorporated the **con**centration and **con**sequence aspects. An evaluation of the passive dispersion module of GASCON2 was then undertaken using the field data. The results of this comparison are presented in Volume 4.

The risk work was referred to as a risk approach rather than a model and that approach was documented in Volume 6. To complete the risk examples, a review of historical failure and toxicological data was required. These statistics and accompanying support information on toxic load are found in Volume 7. There are also three other related documents. Volume 8 is the GASCON2 User Guide, Volume 9 is the Scientific Advisory Board Commentary and Volume 10 is a summary document. The ERCB packaged the 10-volume set and released all volumes in October 1990.

Program Approach

The Technical Committee's design was based on having a generic program consisting of two parts, a tracer and meteorological study. The decision to complete generic testing was made to ensure that any atmospheric dispersion model could be evaluated against the data.

Tracer Study

During an intensive study period, a sulphur hexafluoride (SF_6) tracer gas was released into the atmosphere. This tracer gas was released during low wind speed, stable atmospheric conditions. Downwind SF_6 concentrations were measured at several downwind locations using SF_6 continuous analysers. Cross-wind SF_6 concentration profiles were collected to establish the behaviours and patterns associated with plume dispersion. Meteorological data, concurrent with each tracer release, were obtained to aid in the interpretation of the tracer gas results.

Meteorological Study

The Field Measurement Program was conducted on reasonably flat terrain approximately 20 km from the city of Calgary. The tracer release and sampling occurred during the months of October, November and December 1988. The diffusion meteorological station commenced operation in October 1988 and continued to operate until a 12-month set of data was collected. The meteorological study involved the collection of atmospheric turbulence and wind profile data to obtain meteorological information on the frequency and persistence of low wind speed and low turbulence atmospheric conditions.

Program Overview

Tracer Gas Release and Sampling

On 33 evenings between October and December 1988 when suitable dispersion conditions prevailed, SF_6 was released, with the aid of a fan, to simulate a release of gas escaping from a well or from a ruptured pipeline. A large fan was used for elevated releases and a smaller fan was used for ground level releases. In-plume SF_6 concentrations were then measured by continuous SF_6 analysers mounted in trucks.

A combination of mobile and stationary monitoring was conducted to obtain plume concentration profiles at 700, 1 400 and 2 100 m downwind of the release point. Mobile monitoring provided nearly instantaneous plume profiles, while the stationary monitoring provided plume intermittency information.

For the tracer release, SF_6 was injected into a fan to ensure complete mixing of SF_6 into the simulated plume. Smoke was also injected into this source fan to provide a visible reference from which plume rise information could be obtained. A dozen smoke plume visualization/plume rise tests were conducted prior to sunset using photographic techniques to determine plume heights. During the night when SF_6 was released, smoke was not injected into the fan.

Meteorological Station

A 25 m tower adjacent to the tracer release and sampling sites served as a platform for meteorological sensors. Three axis sonic anemometers at four levels (4, 10, 16 and 25 m) were used to measure mean winds, their variance and fluxes of heat and momentum. A nominal sampling rate of the four sonic anemometers was 10 Hz.

Additional sensors on the tower included back-up propeller anemometers (10 and 25 m) and aspirated temperature sensors (2, 10, 16 and 25 m). The back-up anemometers allowed for comparison to the more sophisticated sonic systems. In addition, measurements of net radiation, relative humidity, barometric pressure and soil heat flux were made. All conventional meteorological sensors were sampled at 1 Hz. Three-minute averages from all sensors were archived on a continuous basis. During the tracer tests, the sonic data were archived from the 10- and 25-m levels at the 10 Hz rate.

Supplementary meteorological data were obtained from tethersonde releases conducted during the tracer release and from a monostatic acoustic sounder. Both data sets were analysed to determine stratification of layers.

Data Reduction and Analysis

Data reduction and analysis were a large aspect of the Field Measurement Program. A total of 700 megabytes of raw data were collected during the testing period with an additional 100 megabytes for the 3-minute meteorological data. A 16-member project team, comprised of meteorologists and engineers, worked on the program objectives for over 20 months to complete the analysis on all 12 months of data. It was the opinion of both the project team and the Technical Committee that a significant data set had been collected.

A large effort was made to collect and analyse concurrent SF_6 source, ambient SF_6 concentrations and meteorological data to describe atmospheric transport and dispersion under low wind speed stable atmospheric conditions. Additional effort was made to gain an understanding and a confidence level in meteorological measurements and atmospheric turbulence processes. Special attention was given to documentation of the data analysis, as it and the data set may prove useful to other investigators.

Program Findings

The initial results of the analysis presented in Volume 1 focused on reviewing all the data, rather than the review of case studies. This approach had the advantage of providing an overview of the important processes and a degree of understanding of the significant features of those processes.

Tracer Study

- A significant portion of the cross-wind plume concentration profiles could be reasonably approximated by a Gaussian profile. In many cases the observed concentration profiles were virtually indistinguishable from a Gaussian distribution, while in others the observed profiles were skewed or even bimodal. This information is valuable considering that the Gaussian approximation is the basis of most dispersion models.

- On average, the smallest plume spread values were not necessarily associated with the lowest wind speed conditions, the smallest vertical or horizontal turbulence or the strongest temperature gradients. This finding was contrary to the expectation that the smallest plume spreads would be associated with the lowest wind speed and turbulence conditions.

- Furthermore, the minimum cross-wind plume spreads were not associated with the largest concentrations. The "worst case" did not appear to occur at the low wind speeds. The largest concentration values were associated with wind speeds of around 3 m/s rather than wind speeds of less than 2 m/s.

- The comparison between the predicted and observed instantaneous plume spreads resulted in considerable scatter. For some source configurations and receptor distances, there was evidence that incorporation of a wind shear enhancement increased this performance, however, the best performance was without the wind shear enhancement. Additionally, the time-averaged plume spread observations and predictions tended to have better agreement without the wind shear enhancement term.

- Comparisons of observed SF_6 concentration to values predicted by a simple Gaussian model showed that the simple model was performing well, within a factor of 2 for paired data, 50% of the time. This was considered to be good, considering the amount of scatter and variability in the atmosphere under stable conditions.

- A review of the stationary data indicated that instantaneous peak to 30-minute mean concentration ratios were in the 3 to 7 range and instantaneous peak to 3-minute ratios were in the 1 to 3 range. A further assessment of the stationary data, which is not part of this review, will evaluate concentration fluctuation statistics.

- Further case studies may be able to isolate selected behaviour characteristics and explain any disagreements between predictions and observations.

Meteorological Study

- The objective of the program was to collect tracer data during low wind speed, stable conditions. During the tracer tests, wind speeds were less than 2 m/s for 16% of the time and stable atmospheres occurred 70 to 80% of the time. The collection of tracer data under other atmospheric conditions was also beneficial to the program.

- In addition to the Field Measurement Program data, other data sets were available to evaluate the frequency and duration of low wind speeds under stable conditions. These included the Calgary International Airport and the Acid Deposition Research Program data sets. All three data sets indicated that low wind speeds (less than 2 m/s) occurred around 20% of the time, and if further subdivided into both low winds speeds **and** stable conditions, the frequency drops to around 10% of the time. During that time, the low wind speeds typically persist for approximately 1 hour, and rarely persist for more than 3 hours (only 1% of the time). Because of normal diurnal variations in meteorological conditions, it is not surprising that the conditions do not frequently persist for more than 3 hours.

  Substantiating this meteorological assumption provides valuable information for model application purposes since concentrations predicted downwind often assume that steady-state conditions will persist for 5 to 10 hours. If the model predicts a large concentration a great distance away, such that it takes longer than three hours to get there, it would seem unlikely for that to happen. Model predictions based on steady-state assumptions have to account for persistence.

- With regard to the minimum turbulence issue, it was found that turbulence measurements of σ_θ and σ_ϕ increased with decreasing wind speeds. The product of $\sigma_\theta \sigma_\phi U$ indicates the magnitude of dilution. Small values are associated with smaller

turbulence. For this specific data set, the product tends to take on a minimal winter value in the wind speed range of 3 to 4 m/s. This was a significant finding, one of the unknowns prior to the Field Measurement Program.

- To determine the effectiveness of various stability classification schemes, an evaluation of the STAR (Airport) and other meteorological preprocessors was done. The Pasquill-Gifford (PG) stability class scheme for classifying turbulence in the atmosphere was evaluated using the STAR approach with airport data and another approach using on-site data. The two approaches agreed on the PG class about 50% of the time and were within one PG class about 90% of the time. An alternative meteorological preprocessor based on heat flux was also evaluated. The evaluation indicated that there were difficulties in measuring the heat flux under low turbulence, stable conditions.

- An empirical power law relationship is frequently used to convert atmospheric turbulence measurements and concentrations from one averaging time to another. The evaluation indicated that the power law relationship generally held for averaging periods less than 3 minutes. Prior to the program, this was uncertain. The value for the exponent ranged from about 0.2 to 0.3. This was consistent with the 0.2 value assumed by Alberta Environment.

- The comparison of sonic anemometer data to the conventional propeller anemometer data indicated that the propeller anemometer had limitations in measuring the vertical turbulence under low wind speed conditions.

- A general observation was that care should be taken in the extrapolation of meteorological wind data from one location to another because of site-to-site variations.

Application to GASCON2

- The formulations in the meteorological preprocessor could be reviewed to allow latent heat flux to be incorporated and for heat flux values to be less than the current minimum.

- An alternative vertical profile for stable conditions was proposed which provides better agreement with the field data than currently incorporated into GASCON2.

- Care should be taken when specifying on-site lateral and vertical turbulence values, as these values can vary with height and stability.

- Previous model predictions were estimating the "worst case" at wind speeds less than 1 m/s. This should be reviewed in light of the Field Measurement Program's "worst case" occurring at 3 to 4 m/s.

- A review of the uncertainties, with instantaneous versus time-averaged plume cross-wind speeds, indicated that predictions were typically within a factor of 2 anywhere from 60 to 75% of the time. This same level of performance is the maximum that GASCON2 would be expected to predict.

The findings of the program have provided a level of confidence in atmospheric behaviour that was not present at the onset of the program. There were many findings that supported the current model work as well as other interesting surprises. The quality of data collection and analysis is high and will provide useful research material for atmospheric scientists in the future. All data files and documentation were made available to the public in October 1990.

Communication of Results

The list of acknowledgements indicates that the support of many made this ambitious effort a reality. This support would not have been there without a great deal of communication. As soon as there was an awareness of the plan, many individuals and organizations volunteered time and resources. An early commitment to release all results to the public was made and was undertaken in October 1990. Communication efforts also included newsletters and a trip to the site for the media where landowners Harold and Marion Randall acted as excellent hosts. In fact, they offered a warm welcome to many visitors at the site. (The photos on the next page show some of the newsletters and the media trip.)

In addition to communicating the findings in the local area and Alberta, the ERCB plans to have the scientific information reach other scientists by way of technical papers and presentations at conferences. In October of 1989, a presentation was made to the World Clean Air Congress in Holland outlining the type of study that was undertaken. Plans currently include presentations at conferences and workshops in North America.

ERCB

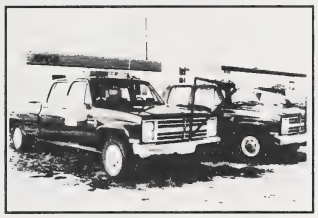
Energy Resources Conservation Board

FIELD MEASUREMENT PROGRAM

February 1989

An Update for Residents of the Kathyrn & Keoma Area

As you know, a team of scientists have been working in your area since September 1988. They have been measuring the dispersion of a harmless tracer gas under "worst case" dispersion conditions; when the atmosphere is stable, with little or no wind. Chinook winds during the fall of '88 caused our testing to continue into December. However, the field portion of this measurement program now is complete and we would like to take this opportunity to let you know what has been accomplished so far.



The air sampling tube running over the top of the truck and down inside the back window is part of the plume monitoring equipment.

Outside air was drawn into the analyzer and the data collected. A portable generator was used to power this equipment.

The Measurement Tests

There were 33 evenings between October and mid-December of 1988 when suitable dispersion conditions prevailed. On these evenings, a harmless tracer gas was released with the aid of a large fan, to simulate the dispersion (or plume) created by gas escaping from a well, or from a ruptured pipeline. Plume measurements were then taken by monitoring devices mounted on trucks. Sometimes, these measurements were taken with a stationary unit parked directly in the tracer gas cloud, while other units were passing through the cloud. At other times, three units were parked in positions such that at least one unit would always be in the gas cloud as it moved back and forth. To aid our record-keeping, a number of photographs were taken, as well as a video tape at various stages of the project.

ERCB

FIELD MEASUREMENT PROGRAM

September 1988

An Update for Residents of the Kathyrn & Keoma Area

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described to you in previous newsletters. Most of the necessary equipment now is in place. ERCB's contractors—**Concord** Scientific Corporation (prime contractor), **Promet** Environment Group and **Indaco** Air Quality Services—will be ready to begin the actual measurements around the end of September.

As we prepare to launch this important program, perhaps it would be helpful if we told you again of the scientific work which will be going on in your area. Beginning early in October, the scientific crew will be **releasing small amounts of a tracer gas—up to 20 times in all—** at the release site. As the gas is **tracing the gas as it spreads out** from the release site, this simulating a re- ed, a large fan will force it y from the ruptured pipeline. What ng is what happens when the gas is sphere and gas using crew. rth

AUGUST 1988

KEOMA AREA

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Energy Resources Conservation Board

Communication Plans Included Newsletters to the Local Area as Well as Residents on the NE Calgary Mailing List.

Field Measurement Program

Photos from Volume 1

Photos from Volume 1

The photo pages from Volume 1 have been included to illustrate the field work. The pictures are presented, in order, without any explanation accompanying each photo. Further details can be found in Volume 1.

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Photo 3.13 - Smoke Plume Visualization With Ground Release Fan On. Side View. ..... Photo Page 3-7

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Photo 4.2 - The Three Identical Continuous Tracer Monitoring Trucks. ..... Photo Page 4-1

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Photo 2.1

Members of the Technical Committee Were at the Site to Ensure it was Appropriate.

Photo 2.2

Photo 2.3

Stations Along the Arc were Marked with Stakes.

Photo 2.4

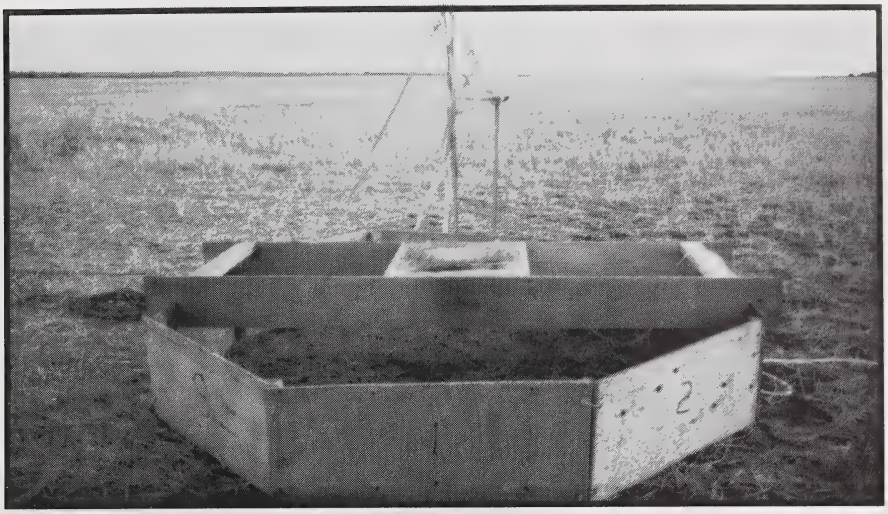

Photo 3.1

Ground Source for Tracer Gas Release.

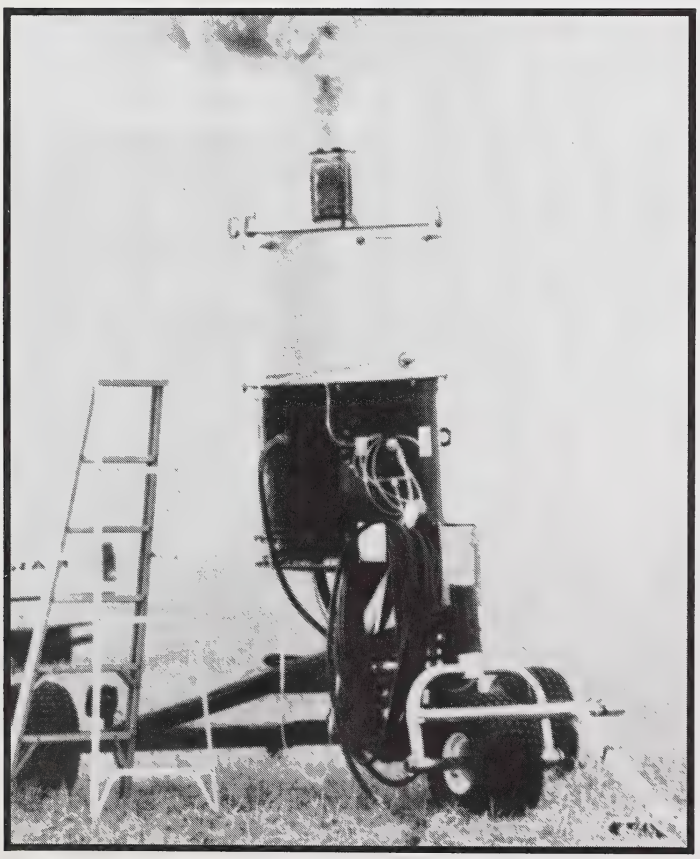

Photo 3.2

Elevated Source for Tracer Gas Release.

Photo 3.3

Fan Calibration Prior to Start of Field Tests.

Photo 3.4

Source Anemometer and Large Fan Used for Elevated Releases.

Photo 3.5

Flow Rate Instrumentation for the Source.

Photo 3.6

The SF_6 Cylinder and Tubing Connectors. The SF_6 had to be Stored Inside the Van, Particularly During Cold Temperatures.

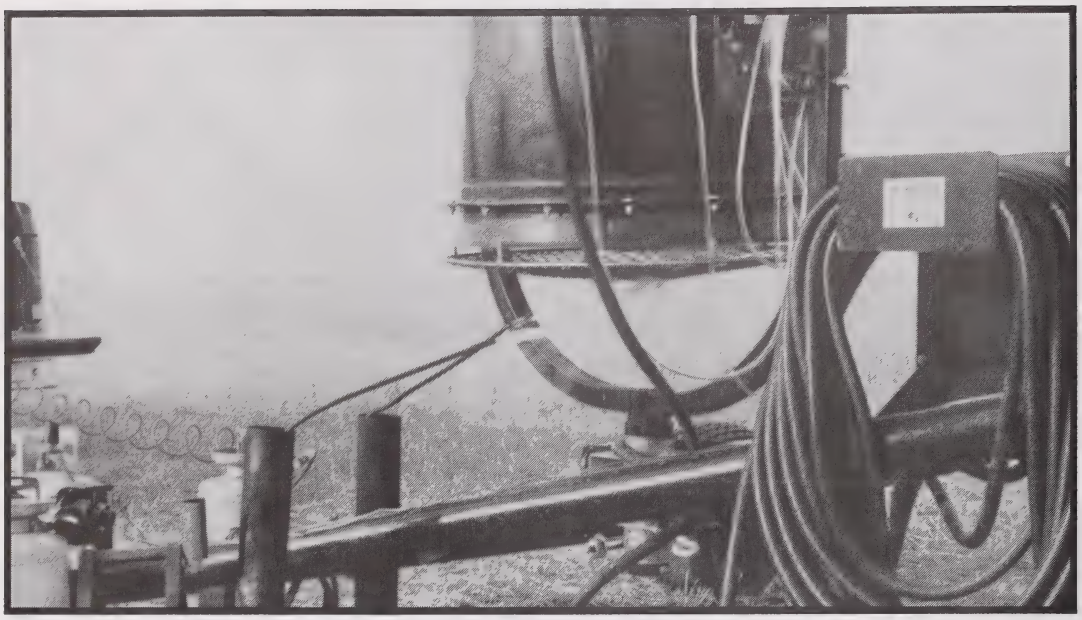

Photo 3.7

Example of Smoke Generation Equipment Tried for the Elevated Release Fan But Not Found Suitable.

Photo 3.8

Example of Smoke Generation Equipment Tried for the Ground Release Fan But Not Found Suitable.

Photo 3.9

Smoke Plume Visualization With Elevated Release Fan Off.

Photo 3.10

Smoke Plume Visualization With Elevated Release Fan On. Photographs and Video were Taken During the Smoke Tests.

Photo 3.11

Smoke Plume Visualization With Elevated Release Fan On. Side View.

Photo 3.12

Smoke Plume Visualization With Elevated Release Fan On. Rear View.

Photo 3.13

Smoke Plume Visualization With Ground Release Fan On. Side View. The Smaller House Fan was Used.

Photo 3.14

Smoke Plume Visualization With Ground Release Fan On. Rear View.

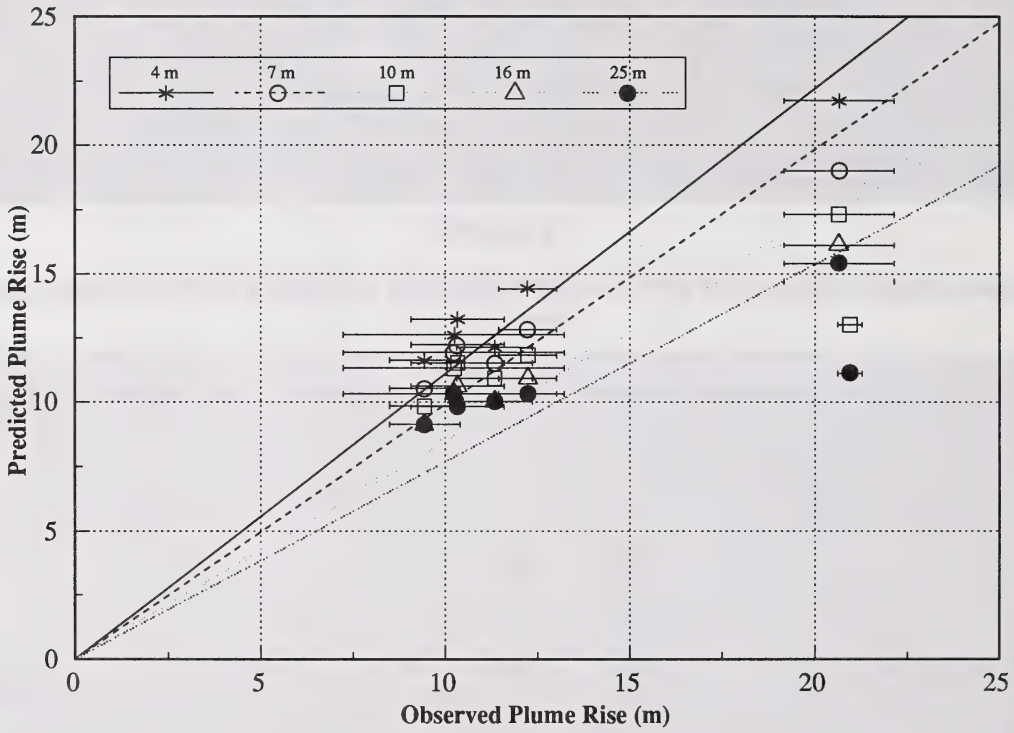

Figure 3.8

Comparison of Predicted and Observed Plume Rises for the Elevated Source Smoke Tests.

Photo 4.1

The Pick-up Box of One of the Tracer Trucks Containing Gas Cylinders and Generator.

Photo 4.2

The Three Identical Continuous Tracer Monitoring Trucks.

Photo 4.3

Full Range Calibrations Before and After the Tests Were Required.

Photo 4.4

Side View of Probe and Tubing Leading Into Analyser.

Photo 4.5

Inside View of Analyser and Portable Computer.

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A View of the Meteorological Trailer, Tower, Acoustic Sounder Enclosure and Tethersonde Tent.

Photo 5.2

A View of the Inside of the Meteorological Trailer.

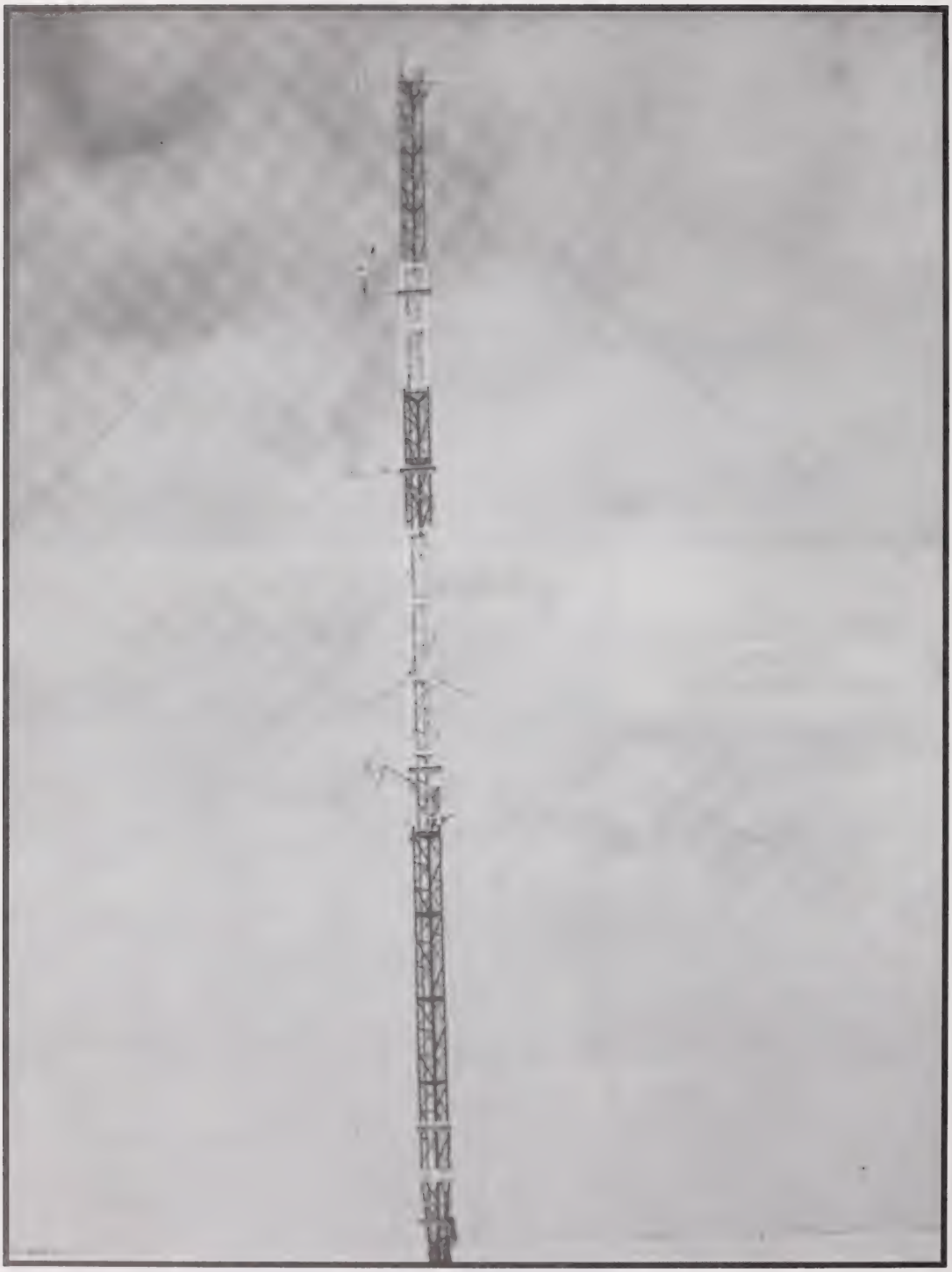

Photo 5.3

The Meteorological Tower Showing All the Instrumentation on it.

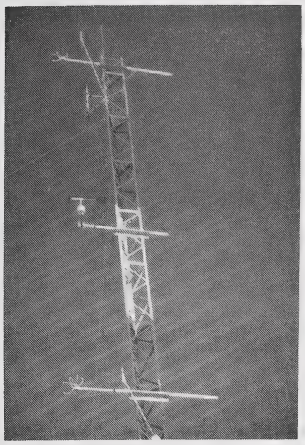

Photo 5.4

16 and 25 m Level Anemometer Sensors. Note the Back-up Equipment.

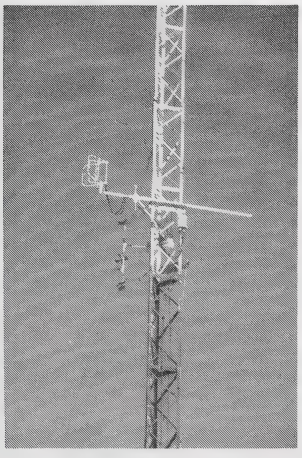

Photo 5.5

10 m Level Kaijo-Denke Anemometer.

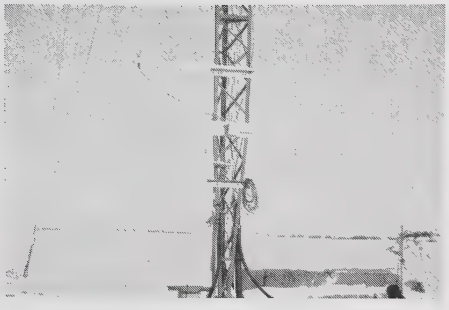

Photo 5.6

4 m Level Applied Technologies Anemometer.

Photo 5.7

As Mentioned in Section 3.3.4, A Mast-Mounted Anemometer was Located at the Source

ERCB Report 90-B
Volume 2

ERCB

Field Measurement Program

Atmospheric Dispersion Tracer Study Under Stable Conditions and Meteorological Study

Appendices to Volume 1
Appendix A

October 1990

Field Measurement Program
Volume 2

Volume 2 contains Appendices A1 and A2 to Volume 1. Both these Appendices deal with mobile tracer data (traverses). Pages 3 to 6 contain samples of the data in Volume 2.

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A2 C/Q Sorted Index for Traverses A-567

Field Test 2
Plume Traverse Statistics
Kathyrn Field Measurement Program

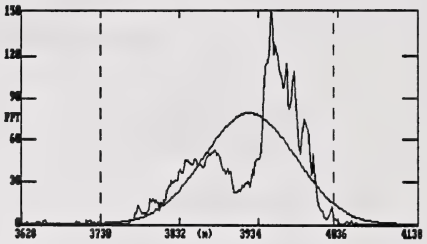
Test Start Time:	20:11	Oct 20 88
Test Stop Time:	00:41	Oct 21 88
Source Type:	Elevated	
Source Location:	South (20:11 to 22:12) West (22:50 to 00:41)	
Analyser A	Status:	Stationary/Mobile
	Arc:	S 1400 m (20:11 to 22:12) W 1400 m (22:50 to 00:41)
		Number of Traverses: 13
Analyser B	Status:	No Useful Data
	Arc:	
		Number of Traverses: 0
Analyser C	Status:	Mobile
	Arc:	S 700 m (20:11 to 22:12) W 700 m (22:50 to 00:41)
		Number of Traverses: 21

SAMPLE

TRAVERSE STATISTICS (T02A03)
File scans: data (185 to 450), moment (250 to 400)
Date : 10-20-1988 Time : 20:32:14 to 20:36:39
Start location: M1 on 1400 m S arc, Source : S Elevated
Power Law Cal. : ppt = 1013.4 *(voltage)^ 1.184

Method	Sigma Y (m)	Mean Abs. Res. (%)	(ppt)	Max conc. (ppt)	Plume center on arc (m)
Moment :	59.3	60.64	27.50	79	3922.9
Hanna :	64.9	52.35	23.85	73	3944.8
Maximum :	31.2	83.89	34.58	151	3949.8

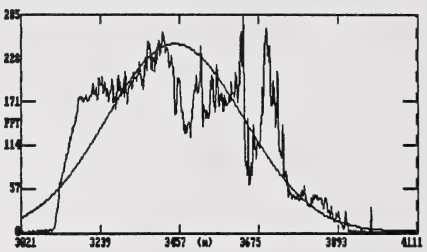
CW int. conc. (ppt m): 11796.71 , % in moment : 99.32
Skewness : -.59 Kurtosis : 2.26
Centroid location : (North 2425.5 m, East 887.6 m)
Transport from 184.6 deg



TRAVERSE STATISTICS (T02A04)
File scans: data (10 to 625), moment (10 to 625)
Date : 10-20-1988 Time : 20:39:29 to 20:49:44
Start location: N8 on 1400 m S arc, Source : S Elevated
Power Law Cal. : ppt = 1013.4 *(voltage)^ 1.184

Method	Sigma Y (m)	Mean Abs. Res. (%)	(ppt)	Max conc. (ppt)	Plume center on arc (m)
Moment :	188.5	25.55	36.72	247	3445.4
Hanna :	214.1	21.99	31.26	217	3438.0
Maximum :	164.3	100.28	112.41	283	3632.0

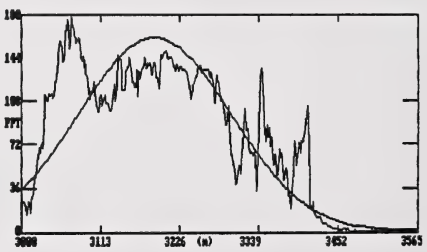
CW int. conc. (ppt m): 116562.2 , % in moment : 100
Skewness : .291 Kurtosis : 2.16
Centroid location : (North 2382.7 m, East 1360.9 m)
Transport from 194.94 deg



TRAVERSE STATISTICS (T02A05)
File scans: data (1 to 380), moment (1 to 380)
Date : 10-20-1988 Time : 20:53:40 to 20:59:59
Start location: K1 on 1400 m S arc, Source : S Elevated
Power Law Cal. : ppt = 1013.4 *(voltage)^ 1.184

Method	Sigma Y (m)	Mean Abs. Res. (%)	(ppt)	Max conc. (ppt)	Plume center on arc (m)
Moment :	108.6	27.16	25.34	160	3190.0
Hanna :	122.2	25.08	21.21	142	3189.8
Maximum :	97.7	89.55	63.10	178	3070.5

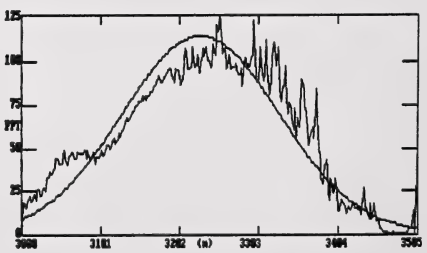
CW int. conc. (ppt m): 43584.23 , % in moment : 100
Skewness : .245 Kurtosis : 2.15
Centroid location : (North 2294.8 m, East 1600.2 m)
Transport from 205.39 deg



TRAVERSE STATISTICS (T02A07)
File scans: data (50 to 380), moment (50 to 380)
Date : 10-20-1988 Time : 21:10:53 to 21:16:23
Start location: L0 on 1400 m S arc, Source : S Elevated
Power Law Cal. : ppt = 1013.4 *(voltage)^ 1.184

Method	Sigma Y (m)	Mean Abs. Res. (%)	(ppt)	Max conc. (ppt)	Plume center on arc (m)
Moment :	101.4	18.55	11.94	115	3228.8
Hanna :	109.1	13.92	8.05	107	3237.9
Maximum :	92.3	25.76	14.70	126	3252.6

CW int. conc. (ppt m): 29165.57 , % in moment : 100
Skewness : -.186 Kurtosis : 2.41
Centroid location : (North 2310.9 m, East 1565 m)
Transport from 203.8 deg



SAMPLE

METEOROLOGY (T02A03)
Date: 10-20-1988 Time: 20:32:14 to 20:36:39 Flow: 2.9 Fan: 25.8 C/Q: 27

TiMet	V4	V10	D4	D10	SigU	SigV	SigW	SigTh	SigPh	Hflux	T2	Tgrad	Nrad	Ustar	z/L
Travel Time Averages (# 3 minute observations = 2)															
20:33	2.49	4.01	173	168	0.29	0.31	0.09	4.38	1.25	-99.0	-99.0	-99.00	-99	0.04	+23.26
30 Minute Averages PG Williamson =-99 PG Bowen =-99 PG Airport = 5															
20:42	2.29	3.43	178	168	0.55	0.34	0.11	5.69	1.87	-99.0	-99.0	-99.00	-99	-99.00	-99.00
3 Minute Values															
20:42	2.03	3.11	176	169	0.36	0.22	0.17	4.04	3.13	-99.0	-99.0	-99.00	-99	0.08	+3.43
20:39	2.66	3.78	170	166	0.38	0.31	0.16	4.65	2.35	-99.0	-99.0	-99.00	-99	0.14	+2.06
20:36	2.89	4.19	168	160	0.30	0.23	0.17	3.14	2.35	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:33	2.52	4.27	168	164	0.12	0.21	0.11	2.77	1.50	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:30	2.47	3.76	178	171	0.15	0.18	0.05	2.81	0.78	-99.0	-99.0	-99.00	-99	0.12	+0.81
20:27	2.45	3.18	188	178	0.20	0.06	0.05	1.15	0.90	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:24	2.13	2.91	187	174	0.17	0.08	0.05	1.57	0.90	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:21	2.08	2.77	190	171	0.12	0.14	0.07	2.94	1.48	-99.0	-99.0	-99.00	-99	0.11	+0.07
20:18	1.88	3.07	187	165	0.17	0.14	0.09	2.62	1.72	-99.0	-99.0	-99.00	-99	0.08	+0.30
20:15	2.04	3.40	173	162	-99.00	-99.00	0.08	-99.00	1.42	-99.0	-99.0	-99.00	-99	0.09	+0.72

METEOROLOGY (T02A04)
Date: 10-20-1988 Time: 20:39:29 to 20:49:44 Flow: 2.9 Fan: 25.8 C/Q: 84

TiMet	V4	V10	D4	D10	SigU	SigV	SigW	SigTh	SigPh	Hflux	T2	Tgrad	Nrad	Ustar	z/L
Travel Time Averages (# 3 minute observations = 3)															
20:42	2.52	3.69	171	165	0.56	0.34	0.17	5.34	2.59	-99.0	-99.0	-99.00	-99	0.02	+100.00
30 Minute Averages PG Williamson =-99 PG Bowen =-99 PG Airport = 5															
20:51	2.18	3.37	178	168	0.65	0.37	0.14	6.22	2.43	-99.0	-99.0	-99.00	-99	0.07	+5.52
3 Minute Values															
20:51	1.37	2.38	207	168	0.67	0.25	0.16	6.07	3.86	-99.0	-99.0	-99.00	-99	0.13	+0.84
20:48	1.71	3.00	183	166	0.20	0.19	0.15	3.54	2.86	-99.0	-99.0	-99.00	-99	0.15	+0.55
20:45	1.92	3.27	178	163	0.38	0.26	0.22	4.56	3.80	-99.0	-99.0	-99.00	-99	0.20	+0.26
20:42	2.03	3.11	176	169	0.36	0.22	0.17	4.04	3.13	-99.0	-99.0	-99.00	-99	0.08	+3.43
20:39	2.66	3.78	170	166	0.38	0.31	0.16	4.65	2.35	-99.0	-99.0	-99.00	-99	0.14	+2.06
20:36	2.89	4.19	168	160	0.30	0.23	0.17	3.14	2.35	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:33	2.52	4.27	168	164	0.12	0.21	0.11	2.77	1.50	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:30	2.47	3.76	178	171	0.15	0.18	0.05	2.81	0.78	-99.0	-99.0	-99.00	-99	0.12	+0.81
20:27	2.45	3.18	188	178	0.20	0.06	0.05	1.15	0.90	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:24	2.13	2.91	187	174	0.17	0.08	0.05	1.57	0.90	-99.0	-99.0	-99.00	-99	-99.00	-99.00

METEOROLOGY (T02A05)
Date: 10-20-1988 Time: 20:53:40 to 20:59:59 Flow: 2.9 Fan: 26.3 C/Q: 54

TiMet	V4	V10	D4	D10	SigU	SigV	SigW	SigTh	SigPh	Hflux	T2	Tgrad	Nrad	Ustar	z/L
Travel Time Averages (# 3 minute observations = 4)															
20:54	1.65	2.64	195	169	0.66	0.39	0.18	8.34	3.79	-99.0	-99.0	-99.00	-99	0.16	+0.35
30 Minute Averages PG Williamson =-99 PG Bowen =-99 PG Airport = 5															
21:03	1.82	2.76	190	170	0.84	0.43	0.15	8.77	3.18	-99.0	-99.0	-99.00	-99	0.08	+3.65
3 Minute Values															
21:03	1.36	1.88	217	181	0.14	0.09	0.04	2.70	1.14	-99.0	-99.0	-99.00	-99	-99.00	-99.00
21:00	1.67	2.06	214	179	0.15	0.12	0.08	3.25	2.17	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:57	1.85	2.19	215	180	0.28	0.22	0.14	5.76	3.75	-99.0	-99.0	-99.00	-99	0.07	+0.37
20:54	1.85	2.00	215	184	0.19	0.22	0.15	6.35	4.34	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:51	1.37	2.38	207	168	0.67	0.25	0.16	6.07	3.86	-99.0	-99.0	-99.00	-99	0.13	+0.84
20:48	1.71	3.00	183	166	0.20	0.19	0.15	3.54	2.86	-99.0	-99.0	-99.00	-99	0.15	+0.55
20:45	1.92	3.27	178	163	0.38	0.26	0.22	4.56	3.80	-99.0	-99.0	-99.00	-99	0.20	+0.26
20:42	2.03	3.11	176	169	0.36	0.22	0.17	4.04	3.13	-99.0	-99.0	-99.00	-99	0.08	+3.43
20:39	2.66	3.78	170	166	0.38	0.31	0.16	4.65	2.35	-99.0	-99.0	-99.00	-99	0.14	+2.06
20:36	2.89	4.19	168	160	0.30	0.23	0.17	3.14	2.35	-99.0	-99.0	-99.00	-99	-99.00	-99.00

METEOROLOGY (T02A07)
Date: 10-20-1988 Time: 21:10:53 to 21:16:23 Flow: 2.9 Fan: 26.3 C/Q: 39

TiMet	V4	V10	D4	D10	SigU	SigV	SigW	SigTh	SigPh	Hflux	T2	Tgrad	Nrad	Ustar	z/L
Travel Time Averages (# 3 minute observations = 4)															
21:12	1.30	2.07	218	198	0.24	0.44	0.07	11.99	1.95	-99.0	-99.0	-99.00	-99	0.07	+2.18
30 Minute Averages PG Williamson =-99 PG Bowen =-99 PG Airport = 5															
21:21	1.60	2.25	218	196	0.45	0.56	0.12	13.97	3.17	-99.0	-99.0	-99.00	-99	0.03	+36.39
3 Minute Values															
21:21	2.12	3.23	200	195	0.39	0.37	0.19	6.56	3.40	-99.0	-99.0	-99.00	-99	-99.00	-99.00
21:18	1.93	2.66	228	208	0.25	0.34	0.16	7.36	3.50	-99.0	-99.0	-99.00	-99	-99.00	-99.00
21:15	1.63	2.52	239	215	0.05	0.20	0.13	4.46	2.96	-99.0	-99.0	-99.00	-99	0.07	+3.73
21:12	1.26	2.31	232	213	0.13	0.21	0.10	5.16	2.53	-99.0	-99.0	-99.00	-99	0.09	+1.50
21:09	1.25	2.20	215	200	0.14	0.16	0.07	4.20	1.84	-99.0	-99.0	-99.00	-99	-99.00	-99.00
21:06	1.36	2.05	211	193	0.22	0.12	0.03	3.24	0.84	-99.0	-99.0	-99.00	-99	0.09	+1.37
21:03	1.36	1.88	217	181	0.14	0.09	0.04	2.70	1.14	-99.0	-99.0	-99.00	-99	-99.00	-99.00
21:00	1.67	2.06	214	179	0.15	0.12	0.08	3.25	2.17	-99.0	-99.0	-99.00	-99	-99.00	-99.00
20:57	1.85	2.19	215	180	0.28	0.22	0.14	5.76	3.75	-99.0	-99.0	-99.00	-99	0.07	+0.37
20:54	1.85	2.00	215	184	0.19	0.22	0.15	6.35	4.34	-99.0	-99.0	-99.00	-99	-99.00	-99.00

SAMPLE

C/Q Index for All Releases.
Sorted in Descending Order.

SAMPLE

Test #	Analyser	Traverse #	Arc	Source	C(mom) / SF_6 Rate	Test #	Analyser	Traverse #	Arc	Source	C(mom) / SF_6 Rate
11	C	15	700	G	11363.070	15	C	10	700	G	5714.285
31	C	8	700	G	11328.890	15	C	23	700	G	5700.000
31	C	12	700	G	11144.890	19	C	29	700	G	5656.757
25	C	9	700	G	10858.140	19	C	33	700	G	5589.189
15	C	7	700	G	10376.660	15	C	15	700	G	5392.592
30	C	9	700	G	10302.430	15	C	13	700	G	5381.111
30	C	8	700	G	9262.223	13	A	8	700	G	5370.370
15	C	8	700	G	8932.608	27	C	22	700	G	5281.609
15	C	5	700	G	8901.087	15	B	16	700	G	5230.909
11	C	20	700	G	8847.619	25	C	13	700	G	5192.683
15	C	11	700	G	8417.582	13	B	11	700	G	5191.463
15	C	6	700	G	8414.772	25	C	14	700	G	5180.000
15	C	14	700	G	7842.352	4	C	39	700	G	5065.979
11	C	18	700	G	7660.937	15	B	18	700	G	4950.000
15	C	22	700	G	7394.643	30	C	2	700	G	4921.839
27	C	18	700	G	7162.352	4	C	35	700	G	4901.031
30	C	6	700	G	7133.333	15	B	17	700	G	4882.143
11	C	14	700	G	7080.000	19	C	15	700	G	4852.702
25	C	15	700	G	6797.561	20	B	5	700	G	4841.333
13	C	4	700	G	6783.750	15	B	8	700	G	4840.659
30	C	4	700	G	6739.506	15	B	15	700	G	4816.364
30	C	3	700	G	6470.114	15	C	19	700	G	4814.814
27	C	17	700	G	6389.286	31	C	4	700	G	4781.395
13	A	7	700	G	6386.420	15	B	13	700	G	4764.814
19	C	32	700	G	6348.052	25	C	17	700	G	4746.511
15	C	9	700	G	6335.555	4	C	31	700	G	4737.500
15	C	12	700	G	6302.174	13	B	18	700	G	4643.373
19	C	31	700	G	6259.459	15	B	12	700	G	4633.333
25	C	16	700	G	6095.348	4	C	24	700	G	4612.121
13	C	12	700	G	6043.902	25	C	8	700	G	4590.244
19	C	30	700	G	6016.216	21	B	4	700	G	4589.411
13	B	23	700	G	5741.463	13	B	12	700	G	4567.073

ERCB Report 90-B
Volume 3

ERCB

Field Measurement Program

Atmospheric Dispersion Tracer Study Under Stable Conditions and Meteorological Study

Appendices to Volume 1
Appendices B through D

October 1990

Field Measurement Program
Volume 3

Volume 3 contains Appendices B to D for Volume 1. Appendix B deals with stationary tracer data, Appendix C deals with source data and Appendix D deals with meteorological data. Pages 3 to 10 contain samples of the data in Volume 3.

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Field Test 2
Stationary Statistics
Kathyrn Field Measurement Program

Test Start Time:	20:11	Oct 20 88
Test Stop Time:	00:41	Oct 21 88
Source Type:	Elevated	
Source Location:	South (20:11 to 22:12) West (22:50 to 00:41)	
Analyser A	Status:	Stationary/Mobile
	Arc:	S 1400 m (20:11 to 22:12) W 1400 m (22:50 to 00:41) Number of 30 minute Periods: 0
Analyser B	Status:	No Useful Data
	Arc:	Number of 30 minute Periods: 0
Analyser C	Status:	Mobile
	Arc:	S 700 m (20:11 to 22:12) W 700 m (22:50 to 00:41) Number of 30 minute Periods: 0

SAMPLE

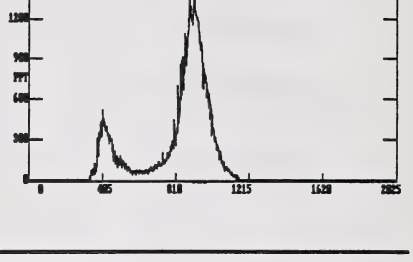
STATIONARY STATISTICS (T03B10)
Scans : 20 to 2000
Date : 10-25-1988 Start Time : 00:14:20
Location: P8 on 1400 m W Source : W Elevated
Abs. Coordinates: (North 2293.8 m, East 1545.9 m)
Transport from 250.47 deg
Power Law Cal. : ppt = 840.2 *(voltage)^ 1.04

PERIOD # 1
Time : 0 : 14 : 32 to 0 : 44 : 31 (1800 s)
Maximum Concentration (ppt) : 1471
Peak (99 perc) to mean ratio : 8.769668
Plume intermittency : .4511111

	Total	Conditional
Mean Concentration (ppt)	148.7111	329.6552
Concentration fluc. intensity (%)	195.6366	108.5209
Skewness	2.547796	1.478186
Kurtosis	8.96451	4.06465

Percentile: 50 99 (Interpolated)
Conc. (ppt) : 0 1304

Percentile:	54.89	54.89	56.67	77.72	86.06	92.78	96.00	97.50	99.78
Conc. (ppt):	2	9	38	165	342	709	1021	1182	1368



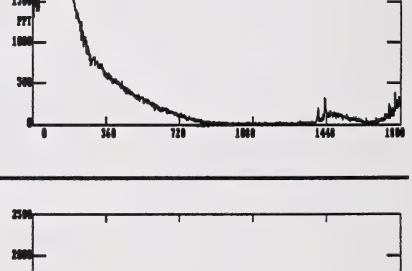
STATIONARY STATISTICS (T03B12)
Scans : 1 to 3601
Date : 10-25-1988 Start Time : 01:00:07
Location: P5 on 1400 m W Source : W Elevated
Abs. Coordinates: (North 2377.6 m, East 1513.1 m)
Transport from 246.79 deg
Power Law Cal. : ppt = 804.2 *(voltage)^ 1.04

PERIOD # 1
Time : 1 : 0 : 0 to 1 : 29 : 59 (1800 s)
Maximum Concentration (ppt) : 2462
Peak (99 perc) to mean ratio : 5.924049
Plume intermittency : .7205555

	Total	Conditional
Mean Concentration (ppt)	377.7311	524.222
Concentration fluc. intensity (%)	160.2231	125.3126
Skewness	1.835359	1.385362
Kurtosis	5.120835	3.540697

Percentile: 50 99 (Interpolated)
Conc. (ppt) : 112 2238

Percentile:	27.94	27.94	41.78	66.28	77.50	86.61	91.56	94.50	99.61
Conc. (ppt):	2	10	50	237	516	1128	1666	1948	2277

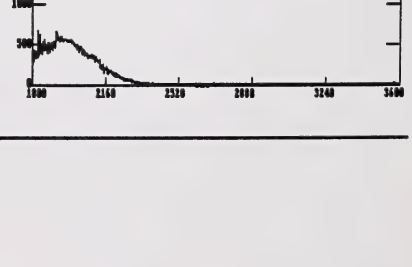


PERIOD # 2
Time : 1 : 30 : 0 to 1 : 59 : 59 (1800 s)
Maximum Concentration (ppt) : 679
Peak (99 perc) to mean ratio : 6.361264
Plume intermittency : .2944444

	Total	Conditional
Mean Concentration (ppt)	93.88834	318.866
Concentration fluc. intensity (%)	188.714	58.57035
Skewness	1.664187	-.2314425
Kurtosis	4.187163	1.669819

Percentile: 50 99 (Interpolated)
Conc. (ppt) : 0 597

Percentile:	70.56	70.56	72.06	76.28	79.83	84.72	93.39	98.22	99.78
Conc. (ppt):	2	7	26	96	184	354	490	558	636



SAMPLE

Summary of Fan Calibration Data

Date	# of Screens	Run #	Pressure RMS (inches H_2O)	Pressure AVG (inches H_2O)	Exit Velocity (m/s)	Momentum Velocity (m/s)	Magnahelic Reading (Pascal)
Oct 5, 1988	Two	1	0.92	0.87	20.91	20.24	N/A
Oct 5, 1988	One	2	0.98	0.94	21.68	21.14	N/A
Oct 5, 1988	None	3	1.42	1.30	26.10	24.95	N/A
Oct 5, 1988	None	4	1.65	1.51	28.18	26.95	N/A
Oct 7, 1988	Two	1	0.66	0.63	17.79	17.38	183.0
Oct 7, 1988	One	2	0.98	0.92	21.62	21.00	215.0
Oct 7, 1988	None	3	1.35	1.26	25.39	24.47	371.0
Oct 7, 1988	None	4	1.55	1.41	27.23	26.01	265.0
Oct 10, 1988	Two	1	0.78	0.75	19.26	18.84	195.6
Oct 10, 1988	Two	2	0.81	0.76	19.62	18.96	185.6
Oct 10, 1988	One	3	1.04	0.98	22.23	21.62	200.6
Oct 10, 1988	One	4	0.99	0.94	21.69	21.20	201.3
Oct 10, 1988	None	5	1.32	1.22	25.04	24.09	258.0
Oct 10, 1988	None	6	1.61	1.50	27.70	26.74	253.0
Oct 11, 1988	None	1	1.46	1.36	26.05	25.12	N/A
Oct 11, 1988	None	2	1.62	1.51	27.51	26.63	N/A
Oct 11, 1988	None	3	1.52	1.36	26.66	25.25	N/A
Oct 11, 1988	Two	4	0.85	0.80	20.00	19.37	260.0
Oct 11, 1988	Two	5	0.83	0.77	19.70	19.01	270.0
Oct 11, 1988	Two	6	0.99	0.92	21.54	20.82	270.0
Oct 11, 1988	None	7	1.40	1.31	25.74	24.88	375.0
Oct 11, 1988	None	8	1.69	1.57	28.27	27.26	370.0
Oct 11, 1988	None	9	1.49	1.34	26.53	25.19	370.0

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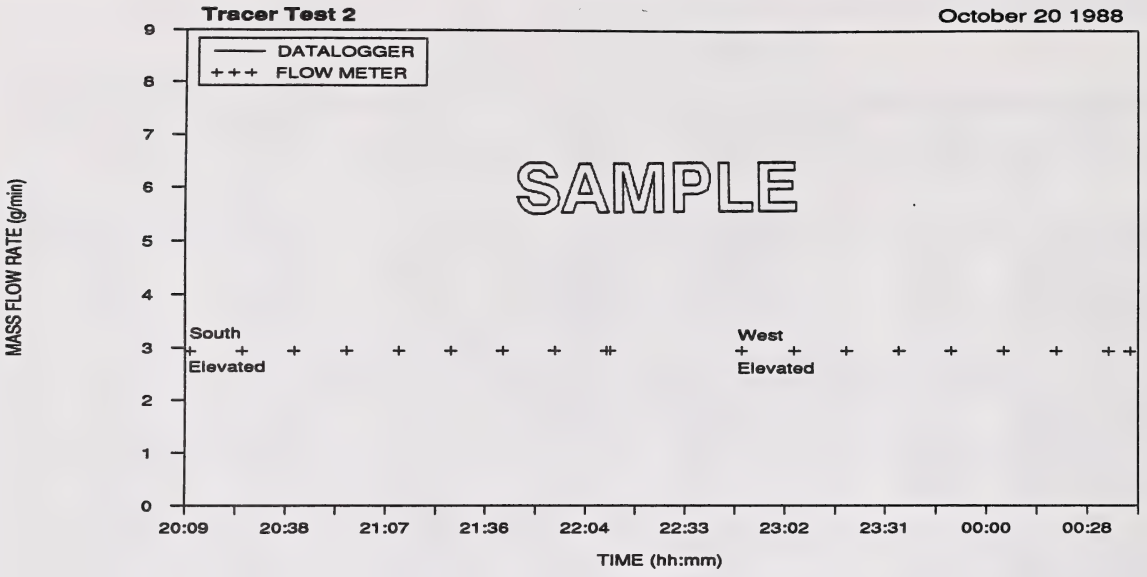


Figure C4.1

Source Mass Flow Rate for Test 2.

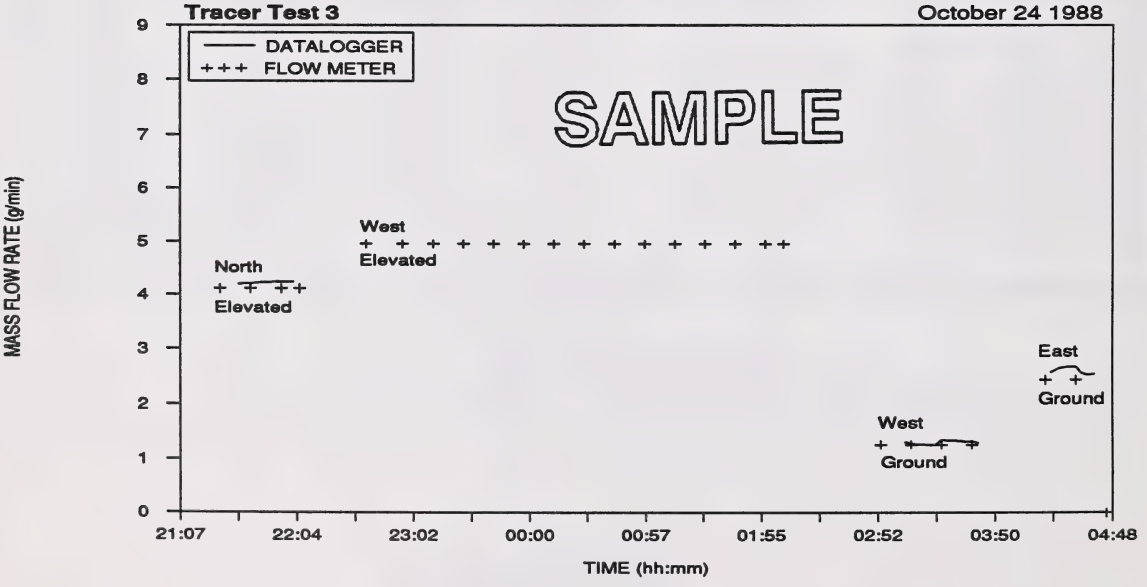
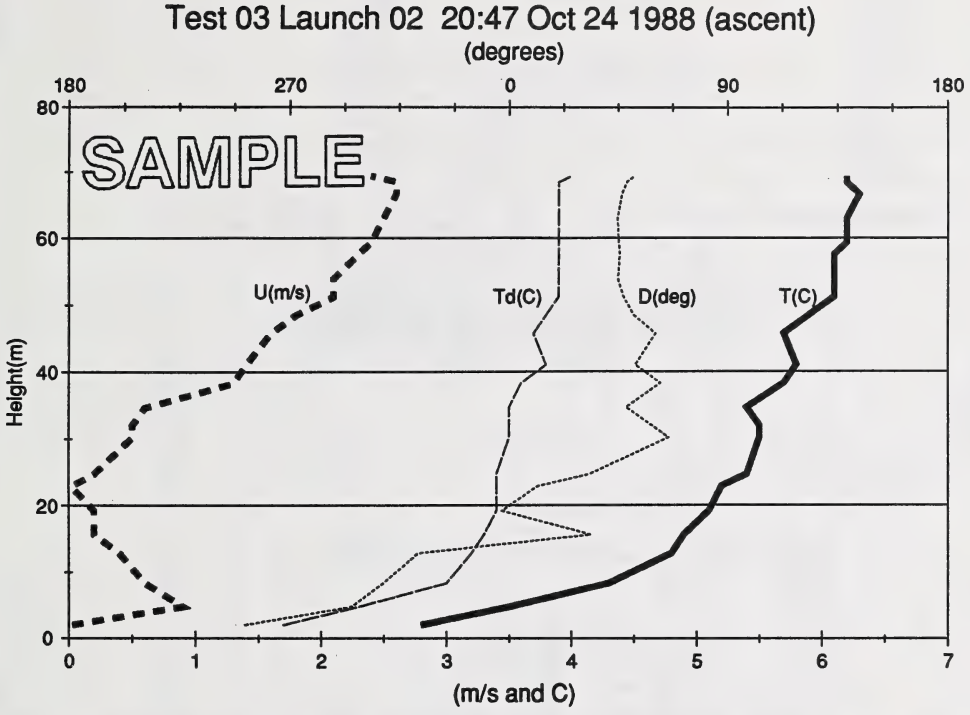
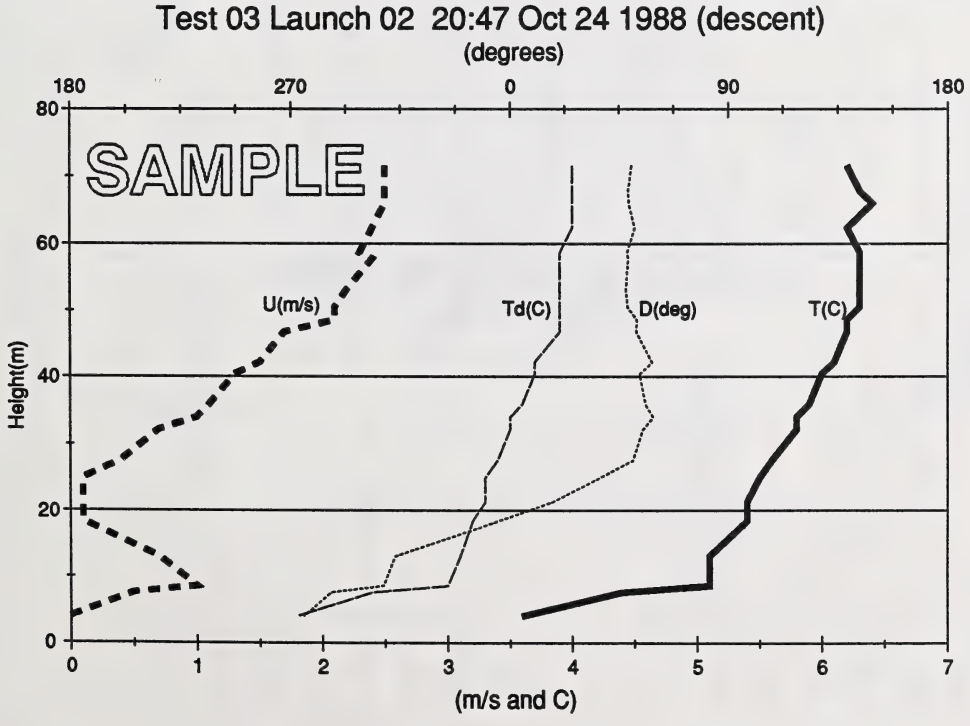


Figure C4.2

Source Mass Flow Rate for Test 3.

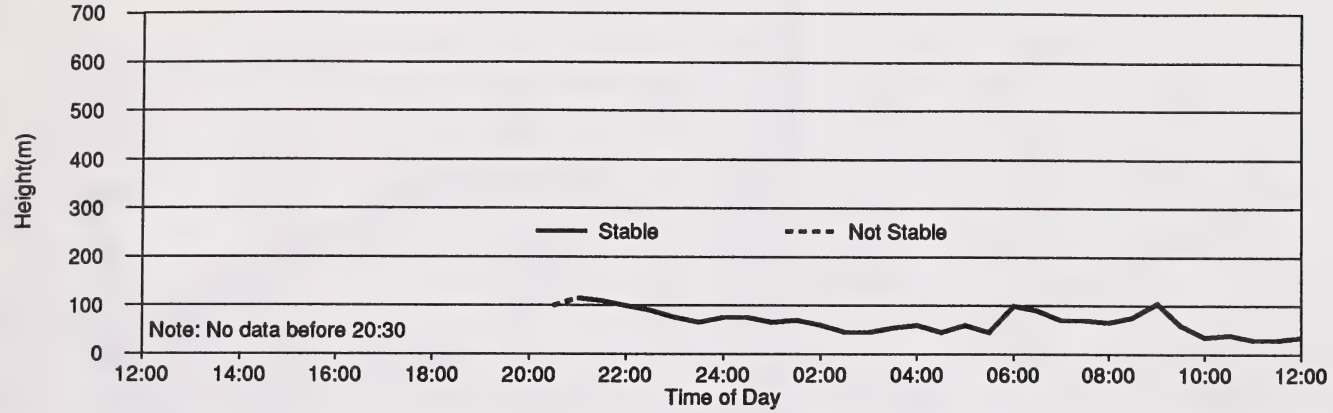
Tethersonde Data





Acoustic Sounder Data

November 4 - 5, 1988



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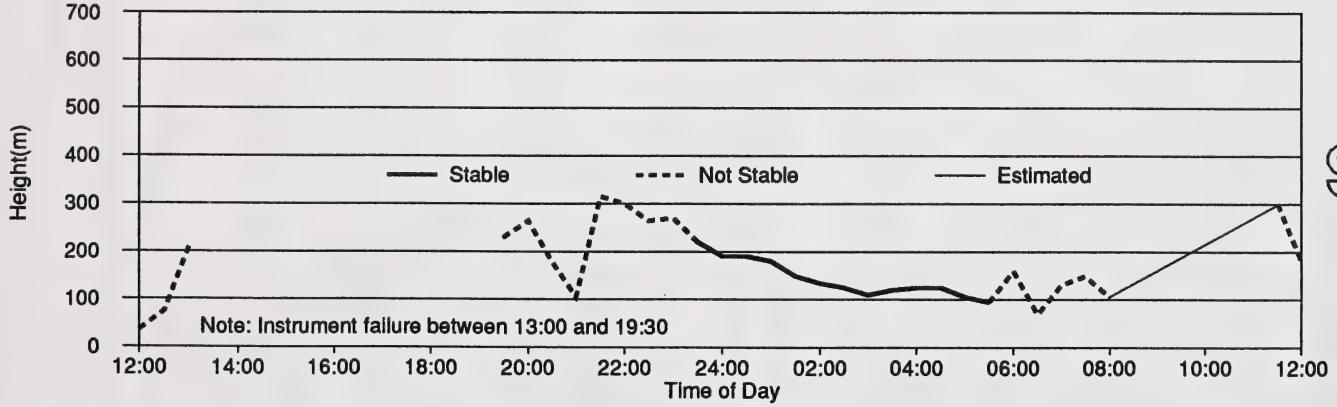

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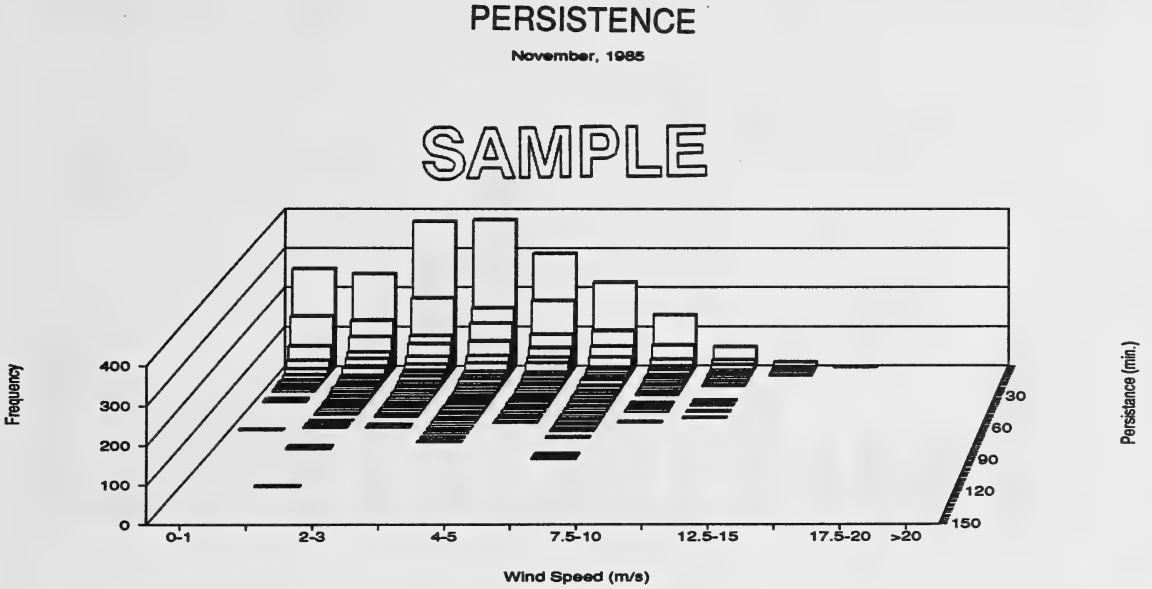
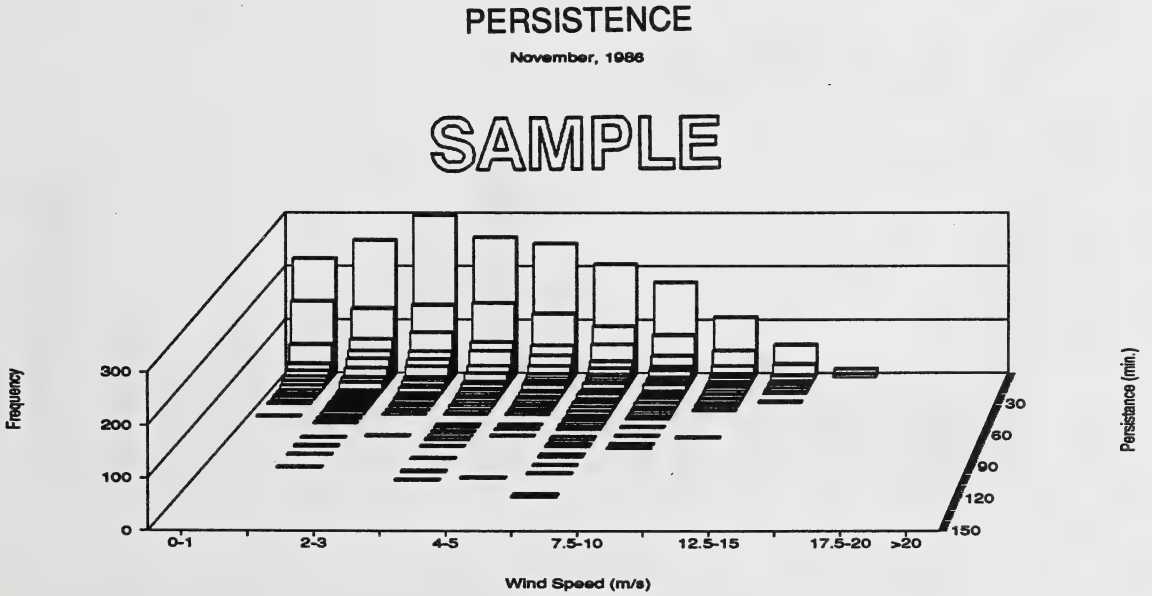
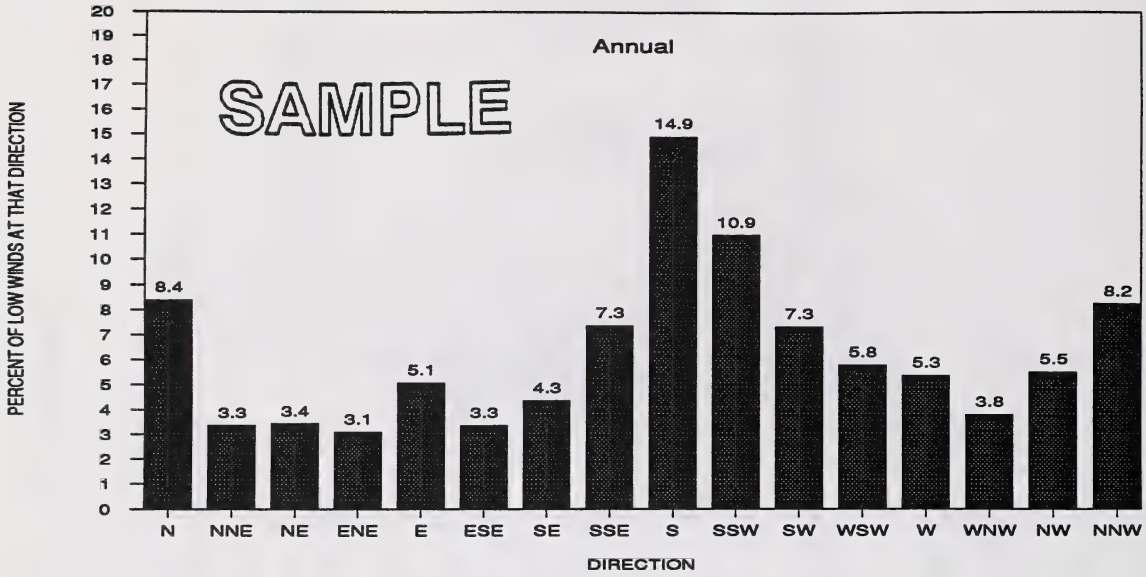


ADRP Persistence Data for November 1985.



ADRP Persistence Data for November 1986.



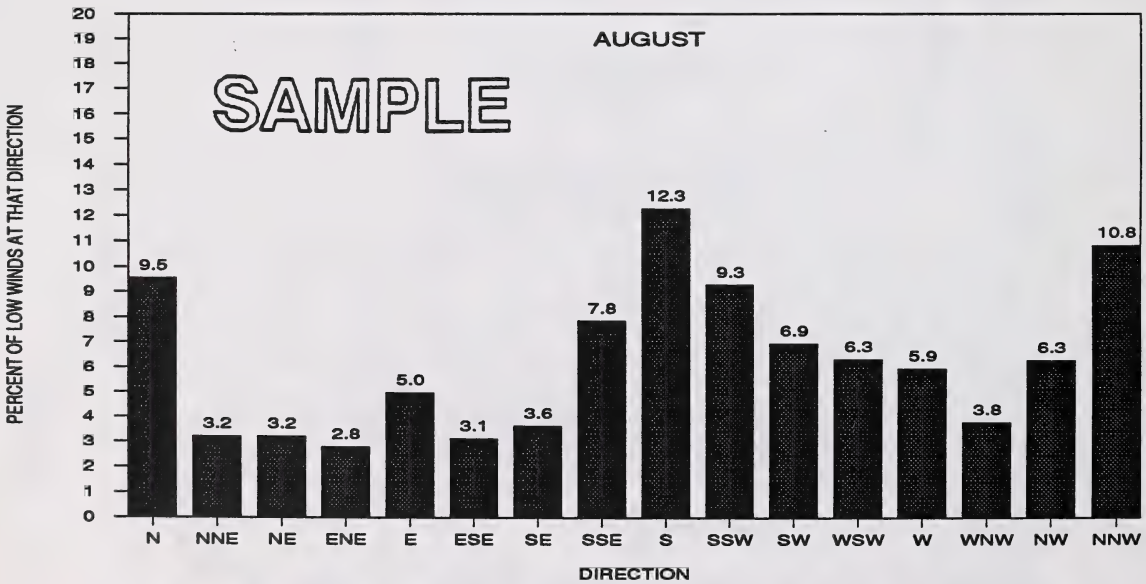


Figure D4.1

Calgary International Airport Wind Direction Frequency Distributions for Periods of Low Wind Speeds (0 to 3 knots) from 1980 to 1984

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Volume 4

ERCB

Field Measurement Program

GASCON2 Evaluation

October 1990

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There are three groups of people who deserve recognition for their efforts during the evaluation of GASCON2. They are the working team, the Advisory Group and the Scientific Advisory Board (SAB). The many extra hours of effort these people contributed are greatly appreciated.

The Working Team

The Project Co-ordinator	Lynda Holizki, who provided a link to all aspects of the project, was assisted by the following:
From the ERCB Environment Protection Department	Stephen Skarstol and John Sutherland, who spent enormous amounts of time correlating model predictions with the various field data.
	Ian Dowsett who developed the Input Preprocessor for the evaluation.
	Richard Wright and Ann Elahee, who were responsible for the typing and technical editing of the report.
From Indaco Air Quality Services	Touche Howard, who provided invaluable service as the technical adviser throughout the evaluation.

The Advisory Group on Model Evaluation Approach

Alberta Environment	Randy Angle and Steve Sakiyama, who were key individuals in establishing protocol for model evaluation.
From Indaco Air Quality Services	Brian Lamb, who is a professor at Washington State University, has been involved in numerous tracer field and model comparison studies. Brian provided excellent advice on the methods for comparisons between field data and that predicted by the models.

The Scientific Advisory Board Commentary on the Final Report

Scientific Advisory Board

The members of the Scientific Advisory Board (SAB) for their peer review and contributions at various stages during the project. The SAB members include R. Angle, R. Purvis, R. Rogers and D. Wilson.

The SAB received input from members of the Field Measurement Program Technical Committee: H. Brown, S. Djurfors and K. Hage.

Others members of the project team were also involved and are acknowledged in Volume 1.

GASCON2 Model Evaluation Summary

Introduction

The Energy Resources Conservation Board (ERCB) commissioned Concord Environmental Corporation to develop the GASCON2 model in 1986. The model estimates the ground level H_2S and SO_2 **con**centrations and **con**sequences in the event of an uncontrolled release from a well blowout or pipeline rupture. The ERCB also managed a Field Measurement Program where actual field data were collected in a simulated well blowout situation. These field data were then used to make comparisons to the following three models:

- GASCON2 July 1990 Evaluation — Section 4
- GASCON April 1990 Evaluation (on 1987 version) — Appendix A
- Simple Gaussian Evaluation — Appendix C

All three model evaluations are contained in this volume, however this summary provides the results for GASCON2 in more detail with a comparison of GASCON2 to the simple Gaussian model. Generally, the GASCON2 model performed better than the original 1987 version of GASCON. The comparison to the simple Gaussian model showed that the performance depended on the source configuration and distance to receptor. It was for this reason that the GASCON2 evaluation was divided into an analysis of ground/elevated and by arc location.

The US Environmental Protection Agency (EPA) is one of the regulatory agencies with a published model evaluation protocol. The protocol was for evaluating time-averaged model predicted concentrations against field observations. However, the Field Measurement Program was designed to collect instantaneous data under passive dispersion conditions rather than time averaged data (see page E-7). Therefore, considerable effort had to be made to ensure that the most appropriate comparisons were made. Another important issue was the type of analysis. The EPA protocol was established for unpaired data analysis; however, the field data collected appeared to lend itself to both a paired (in time and space) and unpaired data analysis. After the evaluations were complete, the highest level of confidence remained with the unpaired data analysis approach.

The most informative plots from all the evaluations are the Figures Sum.1 and Sum.2. These show the observed, simple Gaussian and GASCON2 normalized concentrations on one plot. The findings are discussed in that section.

Data Analysis and Reduction

The Field Measurement Program collected gas concentrations, plume spreads and meteorological data for both traverse (mobile) and stationary monitoring but only traverse data were used in this evaluation. A total of 846 traverses were made over 33 nights and corresponding model runs were made for each traverse. The predicted concentrations were compared to the 846 observed field concentrations. As mentioned, GASCON2 predicts 3-minute concentrations and the tracer traverse data provide essentially instantaneous maximum concentrations.

Model performance can be measured using data sets where the predicted and observed values are either paired or unpaired in time and/or space. Paired analysis is useful if the data set is large and an understanding of the model's behavior is desired. This performance can be related to individual meteorological inputs. Comparisons involving values which are not paired in time and/or space are of particular use when exact matching of meteorological inputs is not available or is uncertain and when the primary goal is to determine the ability of the model to predict the maximum concentrations that may occur. This evaluation addressed both of these methodologies; however, as mentioned the unpaired proved to be most informative.

Model Evaluation Approach

GASCON2 (Alp *et al* 1990) is a computer-based model which can estimate exposure zones for an uncontrolled sour gas release under a number of different scenarios. Data obtained from the Field Measurement Program were used to evaluate this model's performance. In addition, comparisons were made to a simple Gaussian model which was used as a base model because of its simplistic nature.

Although GASCON2 is designed to address a number of different ignited (SO_2) and unignited (H_2S) scenarios, this evaluation only measures the performance of a vertical, steady-state, H_2S release (mainly the passive dispersion module of GASCON2). The Field Measurement Program also collected stationary concentration fluctuation data which can be used to evaluate the consequence module of GASCON2, but the analysis of this data is not included in this evaluation.

Additionally, while tracer data were being collected, detailed on-site meteorological data were also collected over the entire test period. The meteorological preprocessing of this data was evaluated in Volume 1 and only general comments on its impact to GASCON2 are contained in this volume. GASCON2 has a module called METCAL that generates similar output to the pre-processor if it is given a value of surface heat flux.

The Field Measurement Program used sulphur hexafluoride (SF_6) as the non-toxic tracer gas. For model evaluation purposes, GASCON2 was altered to allow SF_6 to be the dispersant instead of H_2S or SO_2. A mainframe based model input processor was developed in order that batch runs of the model could be made quickly and efficiently.

GASCON2 Evaluation Results

The results of this evaluation were separated into the paired and unpaired analysis:

Paired Analysis

- The correlation between predicted and observed values was poor. The correlation coefficient (r) was 0.17 for ground release cases and 0.28 for elevated cases.

- When evaluating the percentage of predicted concentrations which fell within a factor of 2 of the observed, 23% of the ground cases and 40% of the elevated cases met this criterion.

- The paired data were sorted by concentration normalized by the release rate (C/Q). This analysis showed a trend towards increasing underprediction for the higher values of C/Q (worst case).

Unpaired Analysis

- The unpaired analysis showed much better results. The EPA model evaluation protocol, using a fractional bias method for the worst-case regimes, was met for both ground and elevated releases at the 700 and 1 400 m arcs. (This protocol is based on the average of an arbitrary number of the highest predicted and observed concentrations being within a factor of 2.

- Plots of sorted normalized concentrations show that for worst-case conditions (highest C/Q values), the model's predictions follow the trend of increasing observed concentrations. GASCON2 tends to track the observed C/Q values - See Figure Sum.1 and Sum.2.

- Unpaired analysis probably represents the most realistic evaluation of GASCON2 because of uncertainties in matching meteorological model inputs to the tracer data as well as meteorological classification of stability conditions.

- The GASCON2 dispersion module can predict worst-case concentrations that might occur during a toxic release with reasonable accuracy (factor of 2).

- It is unclear if GASCON2 can predict plume concentrations at the correct place and time with the same level of accuracy.

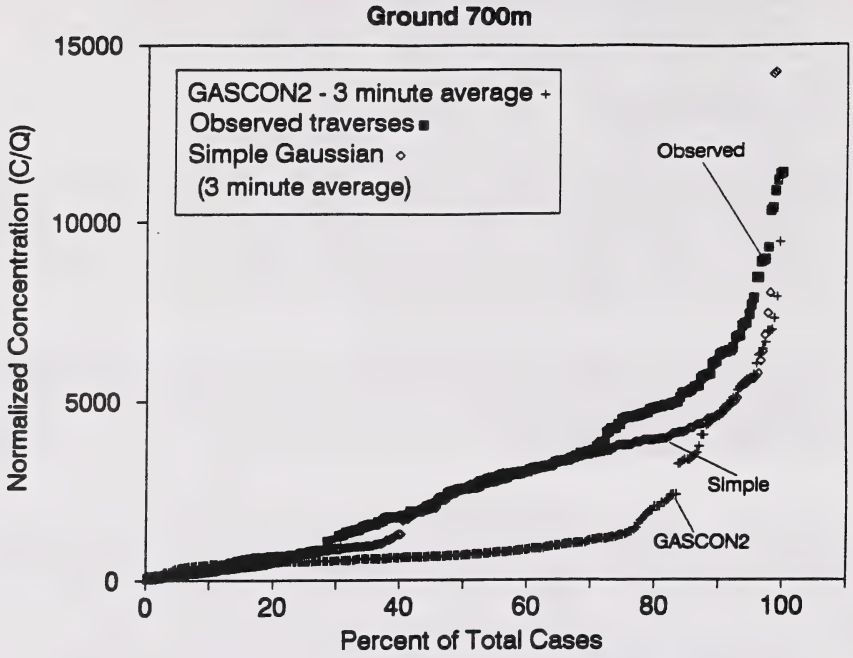
Comparison

Figures Sum.1 and Sum.2 provide the best graphical representation from the entire set of model evaluations plots. These plots are based on the October 1990 version of the GASCON2 model. The model runs are based on 3-minute cross-wind dispersion (sigma y) values. The plots are normalized concentration (concentration divided by the flow rate = C/Q) versus the "percentage of cases".

Ground 700-m Arc

- The simple Gaussian tracked the observed until the higher level of C/Q values were reached. Then, they both tracked approximately in the same manner. It is believed that GASCON2 was not tracking well at the lower end because the model is forcing the neutral stability classification upon predictions that are known to be stable.

- Both models underpredicted slightly. Underprediction of concentration values has been considered serious in the past, given the concentration fluctuation and toxic load issues being dealt with in the consequence module of GASCON2. However, given the differences with respect to instantaneous versus time averaging, this may not be as large a concern.



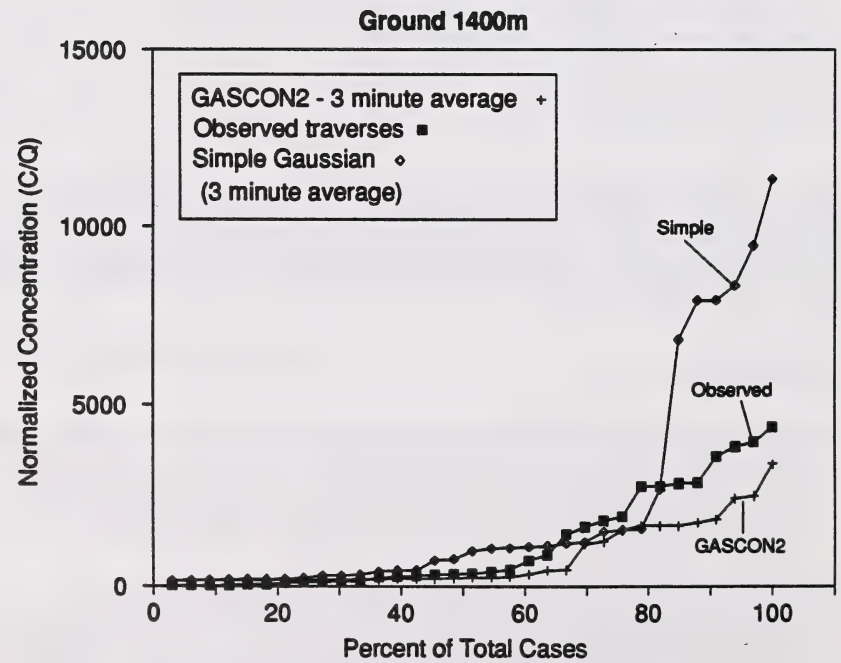


Figure Sum.1

Model Comparison For Ground 700 and 1 400 m Arcs.

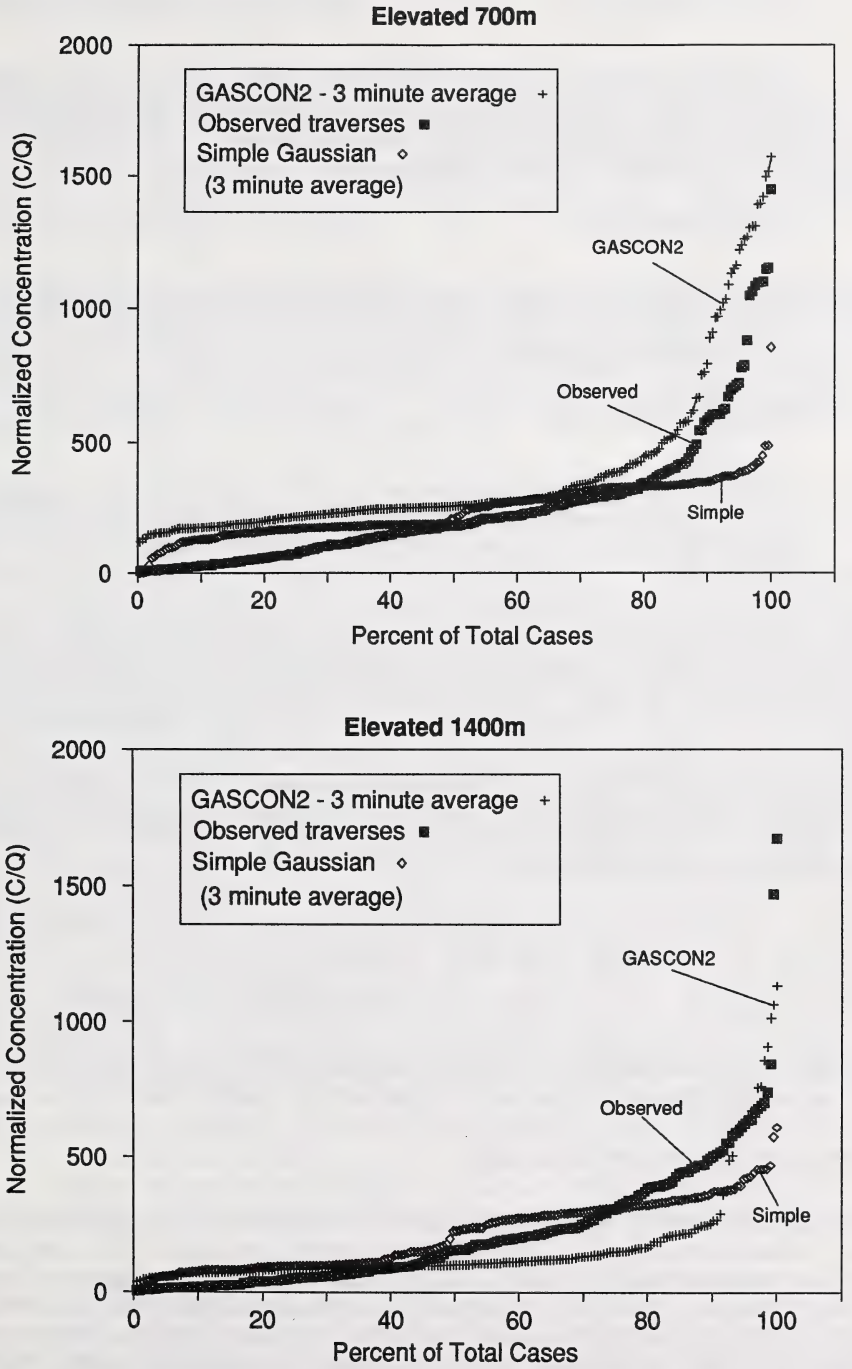


Figure Sum.2

Model Comparison For Elevated 700 and 1 400 m Arcs.

Ground 1400-m Arc

- GASCON tracked the observed values quite well but still slightly underpredicted. The simple Gaussian, on the other hand, overpredicted significantly. Again, the same comment can be made on the underprediction issue with respect to time averaging.

Elevated 700-m Arc

- GASCON2 slightly overpredicted and tracked the observed very well for all concentrations. The simple Gaussian model crossed over the observed line and then underpredicted at high C/Q values.

Elevated 1400-m Arc

GASCON2 crossed over the observed line half way through the data set but overpredicted again at high C/Q values. The simple Gaussian model crossed over about the same point as GASCON2, but then underpredicted at the high C/Q values.

Generally, the "best performance" from a regulatory and public safety perspective would be to slightly overpredict in the high C/Q situation (worst case). In that regard, GASCON2 appears to out perform the simple Gaussian model especially for the elevated releases. In the ground case at 700 m, the simple Gaussian model was doing a better overall job of tracking the observed. This appears to be one of two possible problems with the GASCON2 modules, either the meteorological pre-processor or the ground based sigma y values. These are competing factors that could be looked at in more detail. An important factor to keep in mind is that historically there has been a much larger recorded incidence of the elevated releases compared to the ground case.

From other statistics in Section 4, you will note that GASCON2 was generally predicting within a factor of 2 (25 to 40% of the time). Modelling standards suggest that this is an excellent performance. It is interesting to note that the simple Gaussian model was also doing a reasonable job on the factor of 2 analysis. Since both models have Gaussian-based assumptions, this provides some confidence in the simple approach. This should be good news to most atmospheric dispersion modelling scientists. The Gaussian based models are used by regulatory agencies throughout Canada and the United States. In any event, GASCON2 can handle other complexities such as jet expansion and concentration fluctuations, and this must be kept in mind.

This evaluation attempted to split the analysis into categories such as ground or elevated; however, further work could have been done on a case-by-case basis. Time permitted a review of the worst test night only (Test 15). The same general observations were made as for the entire data set. These were: underprediction until the high C/Q values are reached and then slight overprediction, but with reasonable tracking of the observed. This case study established even more confidence in GASCON2, especially for the highest concentrations. It was noted that the highest concentrations for Test 15 were at around 3 m/s rather than what was originally expected (<2 m/s). The summary of other test statistics is in Section 6 of Volume 1 and this same wind speed observation can be made for those tests even though some high concentrations were at lower wind speeds.

Averaging Time Considerations

Difficulties exist with trying to run a model as it would normally be run with 3-minute averaging time sigmas, and then comparing predictions to instantaneous observations. To emphasize that point, the ground release at the 700-m arc was plotted for various averaging times. Since the exact time cannot be assigned to the observed instantaneous concentrations, the observed line on the plot is identified as "assumed instantaneous". Practically speaking, the time would be around 1 to 30 seconds.

Both the simple Gaussian and the GASCON2 models were run at different sigma averaging times (1 hour, 3-minute and 30-second) in an effort to approach instantaneous predictions. The graphs are not directly comparable; however, if the shorter averaging times are used, the plot shows that model predictions would be closer to the observed. This could alleviate any concerns regarding underprediction for the ground, 700-m case. Unfortunately, this would also have a similar effect on the elevated case.

Comments

GASCON2 development has taken 4 years to reach completion. All of the modules have undergone scientific investigation and sensitivity testing by both the ERCB and Concord staff. The program was also under the scrutiny of the Field Measurement Program Technical Committee and Scientific Advisory Board. Additionally, the passive dispersion and meteorological preprocessing modules have had the added benefit of being evaluated against actual field measurements.

Given the situation, this October 1990 version of GASCON2 was the best effort to incorporate the complex scenarios that the model was designed for. Therefore, the recommendations for further model enhancement, outlined here, are to be thought of as future considerations when research in these areas moves the science forward. This could take some time and meanwhile it is believed that this model evaluation has shown there is sufficient confidence to use the model as it now stands.

Suggested Review/Enhancements

- Review the stability classification criteria. The model appears to be forcing a neutral classification when a stable classification was observed.

- Investigate the GASCON2 sigma y formulations as the predicted sigma y appears to be more constant than the observed values. This could be tied to the neutral stability classification issue as neutral formulations are more constant.

- Investigate the ground-based dispersion formulation. GASCON2 assumes Gaussian in the cross-wind direction, but not in the vertical direction. Since the simple Gaussian model tracked the observed better than GASCON2 for the ground 700-m arc, it may be worth changing the GASCON2 formulation. Since this and the above factors may have competing effects, this change may not be necessary.

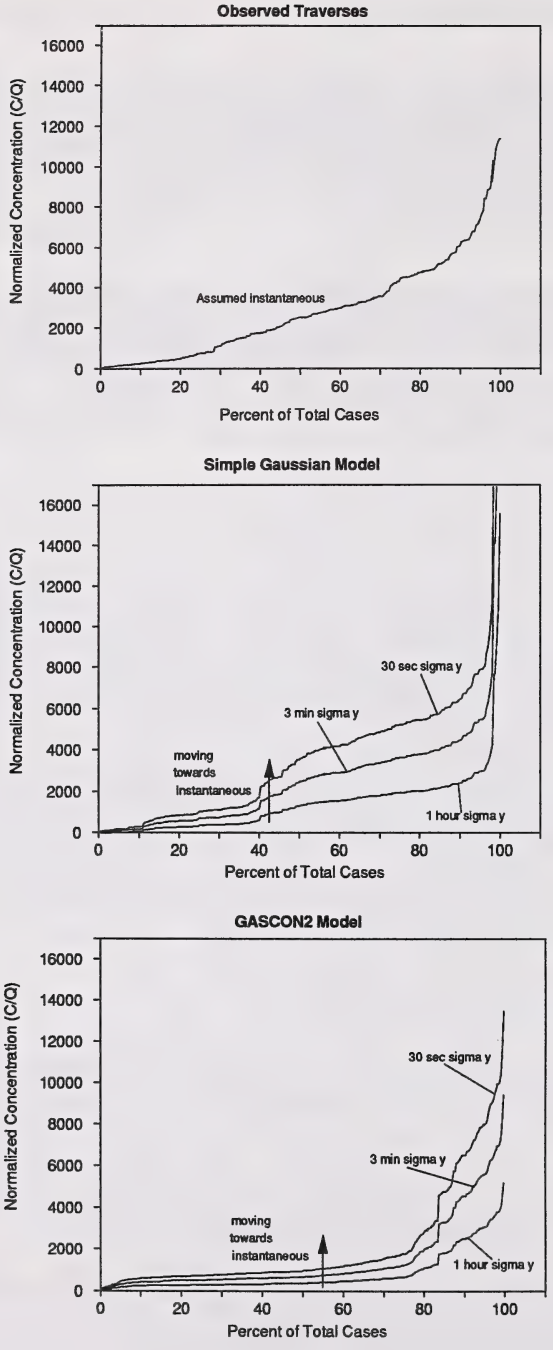


Figure Sum.3

The Importance of Averaging Times (Ground at 700 m).

Conclusions

The comments identify areas for improvement and, not surprisingly, the Field Measurement Program findings came to similar conclusions. Note that the enhancement suggestions are all for the ground-based releases near the source and should be looked at together. The suggestions from both Volumes 1 and 4 warrant some further attention; however, the confidence in GASCON2 was substantially increased with the field work and the model can be used in its current form.

GASCON2 performed reasonably well for all the cases considered. The performance was particularly good for the most important cases, those under consideration for public safety. Generally, it outperformed the simple Gaussian model and tended to track the field observations better. The fact that GASCON2 has many other modules and can deal with a wide range of release scenarios must also be kept in mind. This evaluation was for the passive dispersion module only.

Keep in mind that the ground-based release is the most infrequent historical event and that most releases are expected to be elevated. This observation should be put into perspective before any effort is made to enhance the model. All future model changes, after the public release in October, will be reflected in the GASCON2 User Guide, Volume 8, as updates are generated. Further details of all evaluations are contained in this volume.

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Volume 5

CONCORD
ENVIRONMENTAL

GASCON2

A Model to Estimate Ground-level H_2S and SO_2 Concentrations and Consequences from Uncontrolled Sour Gas Releases

October 1990

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- The members of the Scientific Advisory Board (SAB) for their peer review and contributions at various stages during the project. The SAB members include Dr. D. Wilson, Mr. R. Angle, Dr. R. Purvis and Dr. R. Rogers.

- Another individual, Dr. S. Djurfors, who provided a critical review, particularily of all formulations in the report. His comments were forwarded to the SAB.

- Mr. R.V. Portelli, Concord Environmental Corporation Project Principal, for his overall guidance, support and encouragement throughout the project.

- Those scientists who are referenced in the back of this report for publishing their work and providing the scientific foundation for the work presented in this report.

GASCON2 SUMMARY

The main body of this report is a technical document and the mathematical relationships may be difficult for a non-specialist to assimilate. The GASCON2 summary has been prepared for those who are interested in obtaining an overview of the report contents without going into the level of detail contained within the main body. For those interested in the details, the GASCON2 summary may be passed over to avoid the repetition of material contained in both the main body and the summary.

1 Background

Natural gas is an extremely important resource for Alberta. In 1985, natural gas production averaged 200 million cubic metres per day and generated $ 8.9 billion in revenue. Approximately one-half of the natural gas was derived from sour gas which also produced elemental sulphur. In 1985, Alberta supplied about 8.6 million tonnes of sulphur to domestic and foreign markets which generated an additional $ 957 million in revenue. The production of natural gas and sulphur is expected to continue to play a major role in the Alberta economy for the next few decades.

Implicit in the operation of sour gas facilities is the possibility of an accidental release of sour gas to the atmosphere. For example, during the 14 year period 1975 to 1988, five well blowouts occurred during the drilling of sour wells and seven blowouts occurred during sour gas production. During the same period, at least 30 ruptures were associated with sour gas pipelines. Due to the toxicity of H_2S, a large uncontrolled release upwind and close to a populated area could have serious consequences.

A buffer zone separating sour gas facilities from populated areas and a carefully thought-out emergency response plan can provide a necessary measure of safety when sour gas and residential developments encroach on each other. The difficulty facing planners, regulatory agencies, developers and sour gas facility operators is the determination of buffer and emergency response planning zones that maximize land and resource use without compromising public safety. This difficulty emphasizes the need for a tool which will assist in ensuring that public safety concerns are properly addressed when valuable resource development opportunities are being investigated.

The definition and selection of a concentration criteria can be used to define the edge of a buffer or an emergency response planning zone. The selected value depends on the component of concern (H_2S or SO_2), the exposure period and the corresponding physiological response. For the case of an unignited sour gas release, the toxic constituent of concern is H_2S. If the sour gas release is ignited, then the H_2S is converted to SO_2 which is then the toxic component of concern.

Knowledge of how the concentration changes with downwind distance along with the definition of concentration criteria can serve as a tool to assist land use planners. Mathematical models can be used to estimate ground-level H_2S (or SO_2) concentrations as a function of distance from the uncontrolled sour gas release. Specifically, these models should incorporate H_2S (or SO_2) source conditions which characterize uncontrolled releases and atmospheric dispersion processes.

In Alberta, mathematical dispersion models have been used to estimate ambient H_2S (or SO_2) concentrations which result from uncontrolled sour gas releases. Some of the concepts employed by these models, however, have been identified as being 10 to 20 years out of date with respect to our current understanding of atmospheric behavior. Additionally, these models do not incorporate high velocity jet behavior of the escaping gas near the release point. These deficiencies required the development of a new model specifically designed for uncontrolled releases to ensure that the best available tools are being used to estimate toxic concentrations and consequences resulting from uncontrolled sour gas releases. The availability of a new state-of-the-art model ensures that land use decisions are made on an informed basis.

2 Project Objectives and Organization

The overall objective of this project was the development of a technically sound, model which can be used as a practical tool for estimating downwind distance concentration (H_2S or SO_2) profiles under a wide variety of source and meteorological conditions and the consequences of H_2S emissions to humans. The model was implemented on a computer and went through a detailed evaluation process. This report documents the development and evaluation of the model which is referred to as **GASCON2**. The GASCON2 model estimates H_2S and SO_2 GAS CONcentrations and CONsequences downwind from an uncontrolled release.

The project described in this report was done under contract to the Energy Resources Conservation Board (ERCB) by Concord Environmental Corporation. A Scientific Advisory Board appointed by the ECRB provided technical advice and peer review throughout the project to assure the scientific acceptability of the overall approach. The development of the system entailed the review of modelling approaches and, in some cases, the development of new approaches to address the unique character of uncontrolled releases.

3 Characteristics of Uncontrolled Releases

To appreciate the factors which determine the downwind distance concentration and consequence profiles, it is instructive to review briefly the behavior of an uncontrolled sour gas release as depicted schematically in Figure 1.

The pressure in the sour gas reservoir is typically 100 times that of the atmosphere. When a well blowout occurs, this high pressure gas is released at the well head to the atmosphere as a high velocity jet. Once in the atmosphere, the sour gas goes through the following processes which can dilute the H_2S concentration by many orders of magnitude:

- Within a few pipe diameters of the release point, the pressure of the escaping gases decreases rapidly to that of the atmosphere.
- The escaping gases are very turbulent and air is drawn in and mixes with the high velocity sour gas jet. This mixing or entrainment of air decreases the velocity of the jet.
- The escaping gases will rise due to vertical momentum and natural buoyancy. The height of the plume will be limited by atmospheric stability and wind speed which will cause the high velocity jet to bend over.
- Turbulent dispersion processes will cause the escaping gases to spread in the lateral and vertical directions as the plume moves downwind. The amount of spreading and dilution depends on atmospheric conditions.

There are a number of alternatives which could alter the situation depicted in Figure 1:

- The escaping gases may either be accidentally or intentionally ignited. The ignition of the plume will shift the concern from H_2S to SO_2 and will increase the height of the plume above the ground due to increased buoyancy.
- The gases may not escape in the vertical direction. A valve failure at the well head, for example, may result in a horizontal release.
- Obstacles such as an overhead drilling platform can remove the vertical momentum from the jet, producing a buoyant cloud which subsequently disperses.
- A mixing height in the atmosphere may limit the vertical movement of the plume reducing the dilution properties of the atmosphere. On the other hand, a plume which has sufficient momentum and/or buoyancy can penetrate the mixed layer and disperse above the mixing height reducing ground-level concentrations.
- The amount of hydrogen sulphide (H_2S) in sour gas can vary considerably from one sour gas pool to another. In instances where wells have not yet been drilled the amount of H_2S in the natural gas can be estimated from the gas delivered from nearby wells producing in the same pool. The other constituents of the gas (methane, propane, ethane, carbon dioxide, nitrogen, etc.) are also important in estimating properties of the sour gas (such as density) and in modelling what takes place when the gas release is ignited. Again, these constituents can be estimated from other wells if the well under consideration has not yet been drilled.

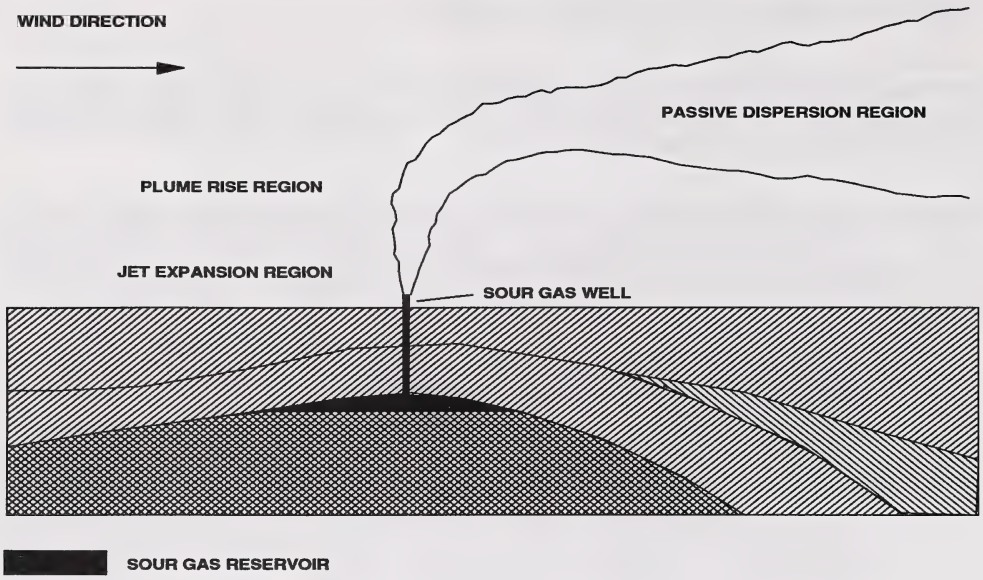

FIGURE 1

Illustration of an Uncontrolled Sour Gas Release.

3.1 Well Blowouts

There are a number of factors which determine the release rate and the initial geometry of escaping gases. For a sour gas well, the surface deliverability of the well will depend on the following flow conditions (Figure 2):

- Casing Flow — Flow up casing or open hole,
- Combined Flow — Flow up annulus and drill pipe or tubing,
- Annular Flow — Flow up annulus only, and
- Tubing Flow — Flow up drill pipe or tubing only.

The jet may be directed at any angle depending on the nature of the failure. All or part of the jet may be deflected by structures present at the wellhead. Four specific cases were considered for this project (Figure 3):

- Downwind Jet — Horizontal jet pointing downwind,
- Vertical Jet — Vertical jet,
- Upwind Jet — Horizontal jet pointing upwind, and
- Cloud — Cloud (jet has lost momentum).

A well blowout is characterized by a continuous release which can be typically days or weeks in duration.

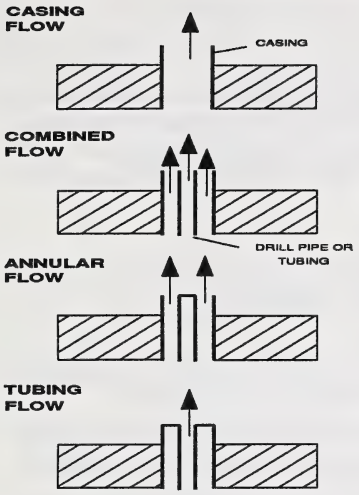

FIGURE 2

Possible Well Flow Scenarios.

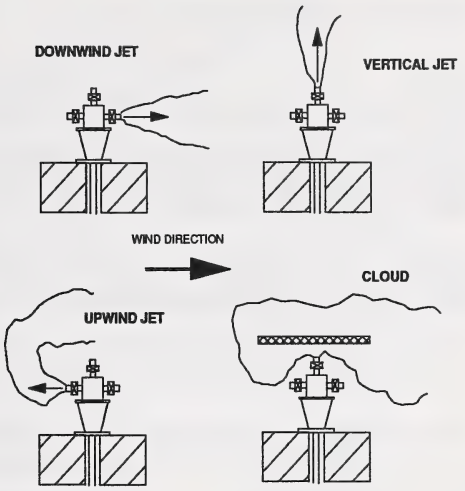

FIGURE 3

Possible Well Release Geometries.

3.2 Pipeline Ruptures

In contrast, a pipeline rupture typically lasts only a few minutes since Emergency Shut Down (ESD) valves isolate the ruptured pipeline segment from the rest of the gas gathering system and limits the amount of sour gas released to the atmosphere. With the presence of ESD valves, the emission rate is characterized by a high initial flow rate which decreases with time as the pipeline is depressurized.

Typical pipeline valve and rupture configurations will lead to different depletion scenarios which will affect the volume and release rate of the sour gas (Figure 4):

- End Pipe Rupture — Rupture adjacent to an ESD valve, all ESD valves operate as designed. One pipeline segment is depleted.
- ESD Valve Failure — Rupture at an ESD valve which fails, all other ESD valves operate as designed. Two pipeline segments are depleted.
- Center Pipe Rupture — Rupture between two ESD valves, all ESD valves operate as designed. One pipeline segment is depleted.
- Decay to Steady State — Rupture in segment next to wellhead, well ESD valve fails, and all other ESD valves operate as designed (An end rupture is depicted).

The last scenario will be characterized by a transient release which will decay to the steady state flow driven by the formation pressure through the well. The other scenarios will be characterized by transient releases which will decay to zero.

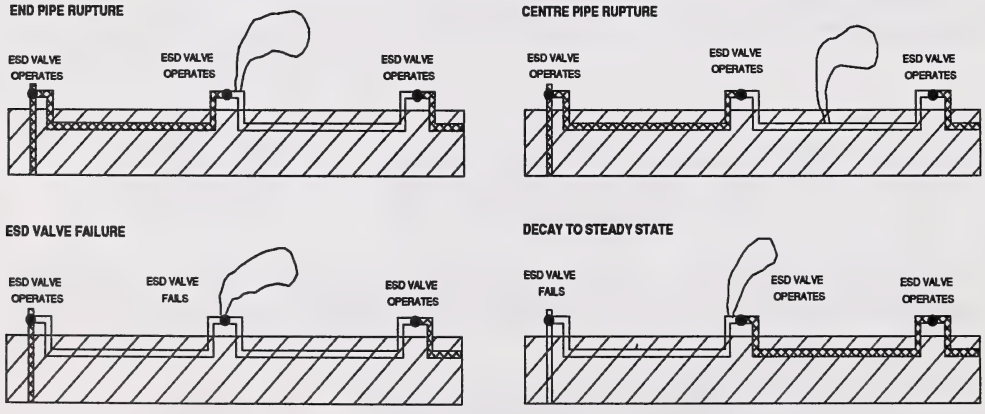

FIGURE 4

Possible Pipeline Rupture Scenarios.

As with a well blowout, the geometry associated with a pipeline rupture will determine the initial behavior of the sour gas in the atmosphere. The cause for the rupture can be external or internal corrosion, metallurgical defects or mechanical (third-party) damage. The release geometries can be broadly categorized as (Figure 5):

- Long Rupture — A section of pipe is removed leading to two sources of gas, each being vented from an opening whose cross sectional area is equal to the cross sectional area of the pipe. Two opposing jets could result from such a configuration.
- Short Rupture — A short rupture or split can occur on the top, bottom or side of the pipe. The cross sectional area of the opening will be typically equal to the cross sectional area of the pipe.
- Leak — Leaks can develop from localized corrosion and are typically pin-sized holes.

Again as is the case for well blowouts, the release geometry can also be described as being an upwind jet, a vertical jet, a downwind jet or a cloud depending on the nature of the release.

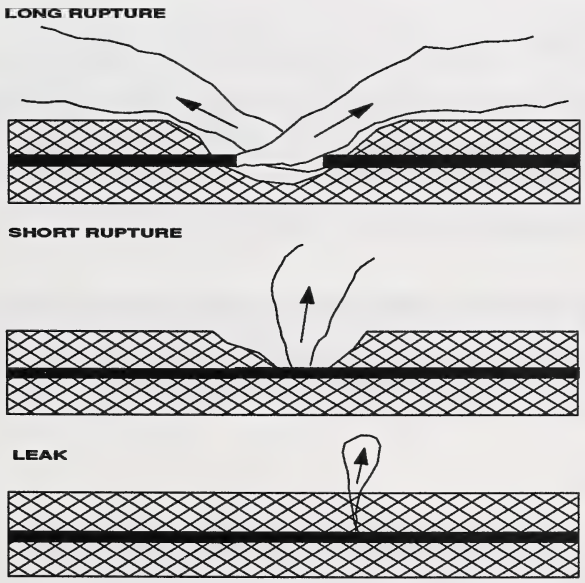

FIGURE 5

Possible Pipeline Release Geometries.

4 Meteorology

The meteorology during an uncontrolled release is perhaps the most important parameter which determines the extent of an exposure zone. The meteorological parameters of importance are:

Wind Speed

Wind speed directly affects the transport of toxic gases in the atmosphere by determining the distance the material moves in a given period of time and the dilution of the material in the along-wind direction. Indirectly, wind speed also affects the rise of the sour gas plume (the faster the wind speed, the lower the plume rise) and the level of turbulence in the atmosphere (the faster the wind speed, the greater the level of turbulence). Increased turbulence levels will increase the dilution of the plume.

Wind Direction

Wind direction determines the direction in which sour gas will be carried and dispersed and the geographical area which will be exposed to the toxic gas.

Temperature

At colder outdoor temperatures the ambient air becomes more dense relative to the sour gas. Because the sour gas is more buoyant in these situations, it will tend to rise higher.

Surface Roughness

Surface roughness is a site-dependent factor which depends on the presence of terrain features such as trees, buildings and crops. An increase in surface roughness will increase the dilution of toxic gas releases. Surface roughness factors are tabulated in many meteorological reference texts under qualitative descriptions of various terrain types.

Stability

Atmospheric stability refers to the level of turbulence in the lowest level of the atmosphere, known as the Planetary Boundary Layer (PBL), within which we live.

Unstable conditions occur when there is significant solar heating of the ground, as one might expect during sunny daytime hours in summer. Under these conditions, large scale convective motions in the form of updrafts and downdrafts are set up in the PBL, causing the rapid dilution of toxic material.

Stable conditions occur when there is cooling of the ground by radiation, as one might expect during the night. Turbulent motions are suppressed in the PBL and toxic gas disperses slowly in these conditions.

Neutral conditions occur when turbulence is neither enhanced (as in unstable conditions) nor suppressed (as in stable conditions). Neutral conditions can occur during transition periods between stable and unstable, and vice versa. They can also occur under high wind conditions.

Mixed Layer Height

This is essentially the height of the PBL in which turbulent mixing takes place. Due to strongly suppressed levels of turbulence at the top of the mixed layer and possible temperature inversions, the mixed layer height can often act as a lid, restricting vertical movement of a sour gas plume. This can reduce the dilution properties of the atmosphere. On the other hand, a plume which has enough momentum or buoyancy to penetrate partially through the mixed layer reduces the amount of toxic gas material to be dispersed within the mixed layer.

The mixed layer height is typically greatest in unstable conditions, when it can be as high as 1 500 to 2 000 metres. The mixed layer height is typically lowest in low wind speed stable conditions, when it can be as low as 50 to 100 metres.

4.1 Meteorological Preprocessor

Wind direction, wind speed and temperature are measured on a routine basis at meteorological stations operated by the Atmospheric Environment Service (AES). AES does not monitor stability, turbulence and mixing heights on a routine basis. Therefore, these parameters have to be estimated from what routine measurements are available and from our understanding of the behavior of the planetary boundary layer. Alternatively, if representative AES stations are not available, then on-site meteorological measurement programs may be initiated during the planning and approval stages of a sour gas facility and for emergency response planning purposes during the operation phase.

A meteorological data preprocessor was developed for this project to estimate atmospheric turbulence levels and mixing height values from routine meteorological observations. This model component is called a preprocessor because it is used before the main component of the GASCON2 model is run. The preprocessor incorporates our current understanding of Planetary Boundary Layer physics.

4.2 Preprocessor Results

For the purposes of illustration, the preprocessor was applied to five years of routine meteorological data from Calgary International Airport for the period January 1 1980 to December 31 1984.

On the average, unstable, neutral and stable conditions were predicted to occur 22, 36 and 42 percent of the time respectively. As expected, unstable conditions occur during day-light hours and stable conditions are primarily associated with night-time conditions. Neutral conditions can be expected any time of the day with a bias to the night-day and day-night transition hours.

Figure 6 compares the preprocessor stability class frequency distributions with those predicted using the more familiar STAR preprocessor approach. The STAR approach predicts unstable, neutral and stable conditions 18, 52 and 30 percent of the time respectively. The preprocessor method predicts more frequent occurrences of unstable conditions. The STAR approach has been found to be biased towards neutral conditions when, in fact, the atmosphere was unstable.

Figure 7 shows the median predicted mixing height values as a function of time of day and season. During the night, the median mixing layer depths are typically 100 m. The mixing depth reaches a maximum between 1600 and 1800 hours (depending on season). During the spring, summer and fall seasons, the preprocessor mixing height results are about one-half the values interpolated for Calgary from seasonal maps prepared from upper air observations.

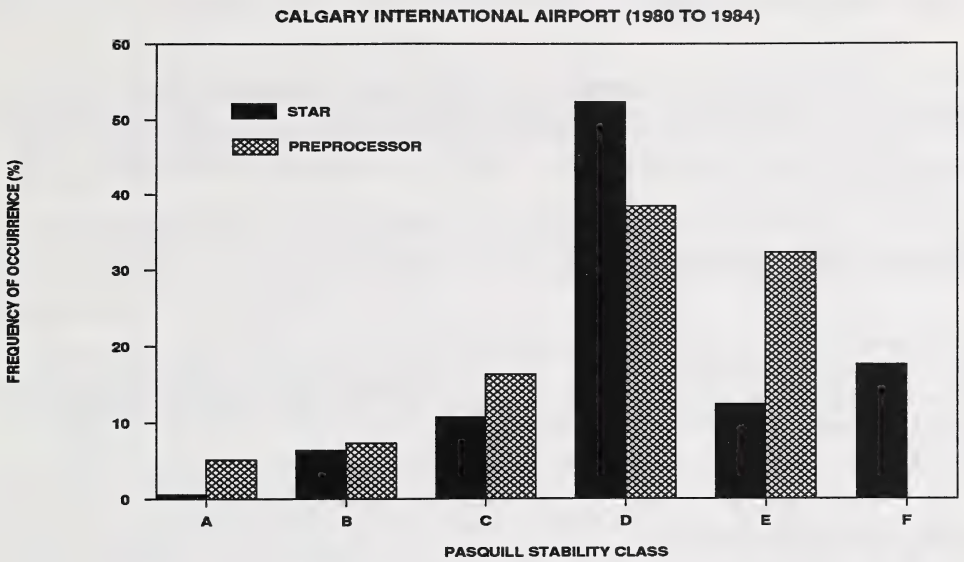

FIGURE 6

Comparison of Pasquill Stability Class Predictions.

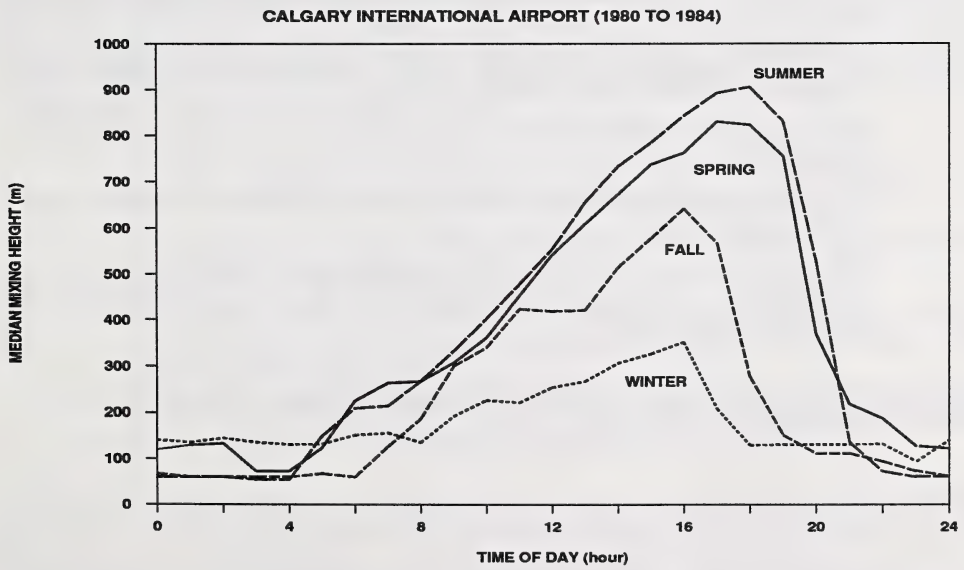

FIGURE 7

Median Predicted Mixing Height as a Function of Season and Time of Day.

5 The GASCON2 Model

The GASCON2 model is used to predict ground-level concentrations of H_2S (or SO_2) as a function of downwind distance and the consequences due to H_2S. The model requires input data characterizing the source release rate, source geometry, meteorology, human vulnerability, exposure time and population density. The GASCON2 model is comprised of six sequential modules.

5.1 Mass Emission Rate Module

The transient release rate of sour gas escaping from a pipeline rupture is estimated using a double exponential blowdown model. This blowdown model has been found to give satisfactory agreement with field data and with more rigorous non-ideal gas models. Transient releases which decay to a non-zero steady-state value can also be simulated in this module.

5.2 Jet Expansion Module

For a well blowout and for virtually the entire duration of a pipeline blowdown, the discharging gas experiences choked flow conditions at rupture exit. The initial behavior of the gas after its release to the atmosphere is treated in five sequential zones:

- The stagnation zone defines the initial conditions at the exit which are determined by the physical properties of the gas, the gas temperature and the area of the release.
- The pressure equalization zone considers the expansion of gas from the sonic underexpanded state to atmospheric pressure.
- The drag zone considers the deceleration of the gas due to impingement with an obstruction.
- The entrainment zone considers the entrainment of ambient air which causes the jet to decelerate.
- The combustion zone considers the potential ignition of the sour gas by accounting for the formation of SO_2 from H_2S and the increased temperature of the combusted gases.

The jet expansion module is used to estimate the effective height of the release, and the initial spread and dilution of the plume.

5.3 Plume Rise Module

As the jet slows down due to the entrainment of ambient air, its behavior begins to resemble that from a conventional industrial stack. The plume will continue to rise due to the vertical momentum which remains in the jet and due to its buoyancy. The latter results from a temperature greater than that of the atmosphere and/or from a molecular mass less than that of air. The plume rise module estimates the trajectory up to its maximum rise. Due to the nature of uncontrolled releases, the plume rise module incorporates more features than those normally used for industrial stacks:

- the ability to estimate the rise of non-vertical releases,
- the ability to estimate the rise of jets directed into the wind (upwind jets),
- the incorporation of ground effects for horizontally released jets, and
- the definition of additional plume rise termination criteria for the integral plume rise approach.

An integral plume rise model was adapted to handle the above mentioned issues, some of which are unique to uncontrolled releases. The final rise predicted by the plume rise module accounts for mixing height effects and also incorporates the commonly used Briggs' analytical plume rise expressions.

5.4 Transient Dispersion Module

This module provides a time history of downwind concentration from a transient release. An effective mass approach accounts for the nature of transient pipeline releases. The effective mass approach allows the steady-state dispersion equation to be used to estimate ambient concentrations from transient sources. This approach allows for more efficient use of computer resources when compared to other approaches which address transient releases.

5.5 Passive Dispersion

Natural turbulent motions in the atmosphere will cause the plume to spread in the crosswind and vertical directions resulting in further dilution of the plume. The amount of dilution depends on the stability of the atmosphere which can vary with time of day, season, height above the ground and on the presence of limiting mixing layers. The passive dispersion module considers elevated and surface releases, and unstable, neutral and stable atmospheres. Features of this module include:

- A plume penetration submodel which allows for the partial penetration of a plume into the free atmosphere above the mixing layer.
- The use of surface-layer similarity scaling for surface sources and the Gaussian plume model for elevated sources.
- The plume spreads for unstable and stable regimes are allowed to vary continuously according to the turbulence parameters obtained from the meteorological preprocessor.
- An effective turbulence level for stable regimes where turbulence has a strong height dependence, approaching a minimum at the mixing height.

The passive dispersion module estimates plume spreads as given by their standard deviations (σ_Y and σ_Z) from the appropriate PBL parameters obtained from the meteorological preprocessor. As mentioned above, this allows the turbulence to vary continuously. This is in contrast to commonly used dispersion models which adopt discrete stability classes and corresponding plume spread formulations.

5.6 Fluctuating Toxic Load and Probit Module

This module accounts for two very important factors in the determination of the consequences to people due to an accidental sour gas release of toxic gas concentration. The first factor is the variation in toxic gas concentration ("fluctuating load") due to the natural turbulence in the atmosphere. The second factor is the human susceptibility to toxic gas exposure ("probit analysis"). Together these two factors give an estimate of the likelihood that people exposed to sour gas during an accidental release would be adversely affected.

Variation in Toxic Gas Concentration

Peak concentrations may be several times the average concentration predicted by the passive dispersion module due to the natural turbulent motions of air in the atmosphere. Toxic loads based on average concentrations are not adequate to model adverse effects since the periods of peak concentrations would be severely understated.

GASCON2 incorporates a current model for concentration variability in its treatment of detrimental effects. Because human vulnerability is based on the toxic load, the model is capable of handling the peak periods of toxic gas concentration during the exposure time.

Human Vulnerability to Toxic Gas

Experiments performed on animals and limited documented incidents of accidental human exposures to toxic gas have indicated that both concentration level **and** exposure time are important in defining the potential for an adverse effect. This potential is called the **toxic load**. The toxic load is similar to the concept of **dose**, in that the greater the toxic load that a person is exposed to, the greater his chances of responding adversely. An increase in **either** toxic gas concentration **or** exposure time will increase the toxic load, however the toxic load is more dependent on changes in concentration than exposure time.

The toxic load concept, and its implementation in human vulnerability modelling, is a large step forward in risk assessment methodology. Whereas previous work has made extensive use of critical concentration levels, and the hazard zones defined by them, the approach used in this study accounts for exposure time effects in a realistic way using the toxic load concept.

If a sour gas well blowout were to occur, the toxic effect of H_2S would depend on the length of time people would be exposed to the toxic gas. This exposure time would strongly depend on the delay time for ignition of the sour gas release from a well blowout or the time to deplete a ruptured pipeline segment.

The potential number of people that can be adversely affected by an accidental sour gas release is dependent on the population density (people per square kilometer) in the exposure zone around a sour gas facility.

5.7 Model Limitations

Before applying any model to solve a specific problem, it is important to recognize the limitations imposed by the model assumptions. The following have been identified as limitations to consider when applying GASCON2:

- Limited Pipeline Release Scenarios. Only End Pipe Ruptures or release scenarios which can be considered as the superposition of two or more End Pipe Rupture cases are evaluated.

- Upwind and Downwind Horizontal Jets. The model cannot evaluate horizontal releases which are oriented at some arbitrary angle lateral to the wind (e.g., cross wind releases).

- Combustion Module Gas Chemistry. The chemistry and physics of the ignited plume assume the sour gas to be comprised of methane (CH_4), carbon dioxide (CO_2) and H_2S only. Other gases are accounted for in a limited fashion by the heat of combustion factor.

- No Condensation Effects. The model does not consider the dispersion and deposition of condensate aerosol clouds.

- Steady state atmospheric conditions. The models do not address transient atmospheric phenomena such as the rapid mixing of a plume above the mixing layer by the growth of the mixing height (sometimes called inversion breakup fumigation) or changes in wind direction.

- Travel times less than a few hours. During periods characterized by light winds, disorganized and recirculating wind flows, the usefulness of dispersion models at distances beyond 10 km is limited. A wind speed of 1 m/s and a distance of 10 km correspond to a travel time of 3 hours.

- Averaging periods ranging from a few minutes to a few hours. The model is designed for estimating three-minute to one-hour average H_2S concentrations and up to three-hour average SO_2 concentrations.

- Flat terrain conditions. Significant topographical features such as large hills and deep valleys can have blocking, steering, channeling, or deflecting effects on the plume trajectory. In the model, moderately rough terrain can be accounted for adopting an appropriate surface roughness value.

- Homogeneous terrain. The models do not address changes in the surface characteristics such as roughness with varying downwind distances.

- H_2S Lethality. Consequence estimates are based solely on H_2S inhalation.

- Population Outdoors and Stationary. Model assumes population is outdoors and does not flee to the protection of a building.

- Average Adult Population. Recommended parameters used to describe human response to H_2S are representative of average adults and may not be applicable to sensitive sub-populations (elderly, children, asthmatics).

For some cases where a model limitation may be an important factor, some indication of ground-level concentrations can be obtained by running the model for different cases which bracket the case to be evaluated. For example, the following limitations may be addressed in this manner: Upwind and Downwind Horizontal Jets, Limited Pipeline Release Scenarios and Homogeneous Terrain Conditions.

6 Selected Model Predictions

Well blowout and pipeline rupture concentration and consequence profiles based on reasonable release parameters are presented. The profiles are based on the following model input values:

Well Parameters

- Sour gas release rate of $240 \cdot 10^3$ m^3/d.
- Release diameter of 52.4 mm.
- H_2S concentration of 30% in the sour gas.

Pipeline Parameters

- Pipeline length of 1000 m.
- Pipeline diameter of 154.1 mm.
- Release diameter of 154.1 mm.
- H_2S concentration of 30% in the sour gas.

Atmospheric Parameters

- Stable atmospheric conditions.
- For unignited releases, a wind speed of 1 m/s and a mixing height of 28 m.
- For ignited releases, a wind speed of 3 m/s and a mixing height of 94 m.
- Flat or gently rolling terrain covered by mature agricultural crops.

The above meteorological conditions represent "base case" conditions. For other atmospheric conditions, the predicted concentration values are expected to be less than the values shown in the figures, but some combinations may produce higher results.

Well Blowout Predictions

Figures 8 and 9 show typical predicted H_2S and SO_2 concentrations which could result downwind from a well blowout. The results indicate that the estimated H_2S concentrations are very sensitive to the type of release but SO_2 concentrations are not. For example, the distance to the 100 ppm three-minute average H_2S concentration can be as large as 4 km for a downwind jet. For a vertical jet, the maximum estimated H_2S concentration is considerably less than 100 ppm. The maximum SO_2 concentration of about 1 ppm is much less than that for H_2S.

Figure 12 shows the probability of receiving a lethal toxic load for various well blowout release scenarios. The downwind jet has the highest probability of lethality while the vertical jet and cloud have the lowest. In other words, for a person located 0.5 km downwind of the well blowout, if the release was horizontal, there would be a 100% chance of fatality. But if the release was vertical or a cloud type, the chance of fatality is zero. Fortunately, experience has shown that most releases are of the vertical jet type.

Surface Pipeline Rupture Predictions

Figure 10 shows the transient H_2S concentration-time profiles for selected downwind distances from the release site. At distances of 1 and 2 km, the average H_2S concentration is estimated to exceed 100 ppm for 4 and 5 minutes, respectively. Figure 11 shows typical peak H_2S concentration profiles which could result from a pipeline rupture. The results indicate that the estimated peak concentrations 2 km downwind are not very sensitive to the type of release. However, near the source, downwind jets give the highest concentrations. The differences depend on the relative plume size and elevation above ground. Horizontal jets do not rise as high as clouds and vertical jets and travel a considerable downwind distance before reaching the final rise.

Figure 13 shows that for the base case pipeline, the downwind jet is the only rupture geometry which results in a probability of lethality greater than zero. This type of release could occur from a rupture in above ground pipe at surface facilities. Experience has shown that most pipeline ruptures occur in the buried pipe. Buried pipeline predictions are sensitive to the emission angle. A typical release angle of 45 ° results in low concentrations of H_2S and no consequences.

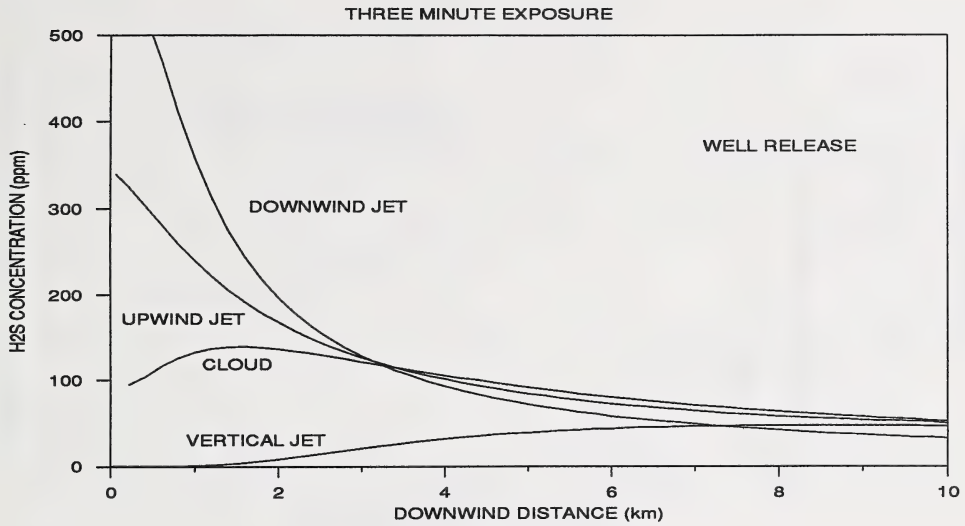

FIGURE 8

Predicted H_2S Concentrations for Selected Well Geometries.

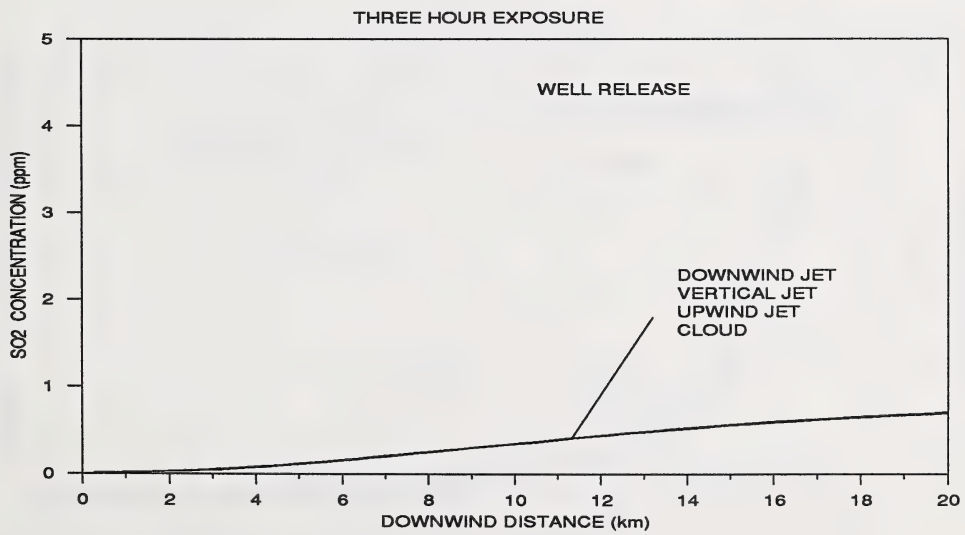

FIGURE 9

Predicted SO_2 Concentrations for Selected Well Geometries.

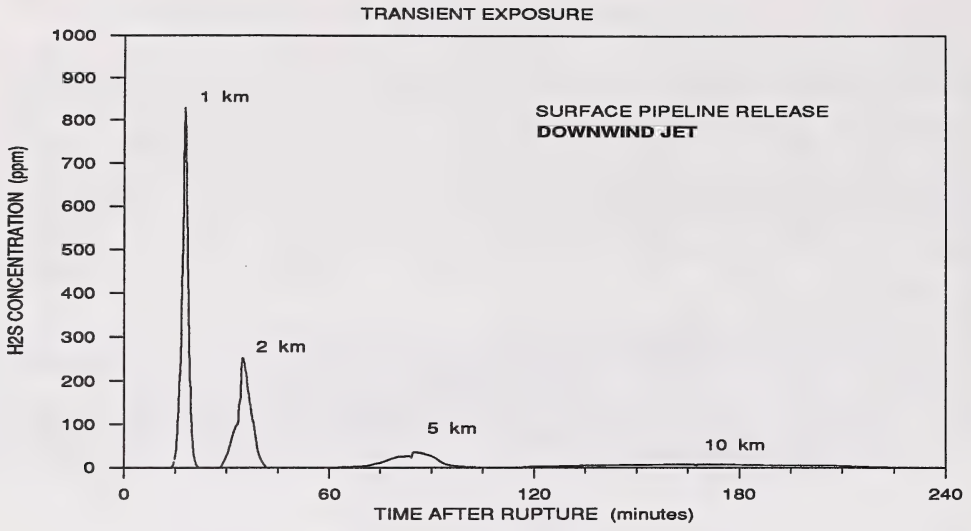

FIGURE 10

Predicted H_2S Concentrations from a Surface Pipeline Rupture as a Function of Time.

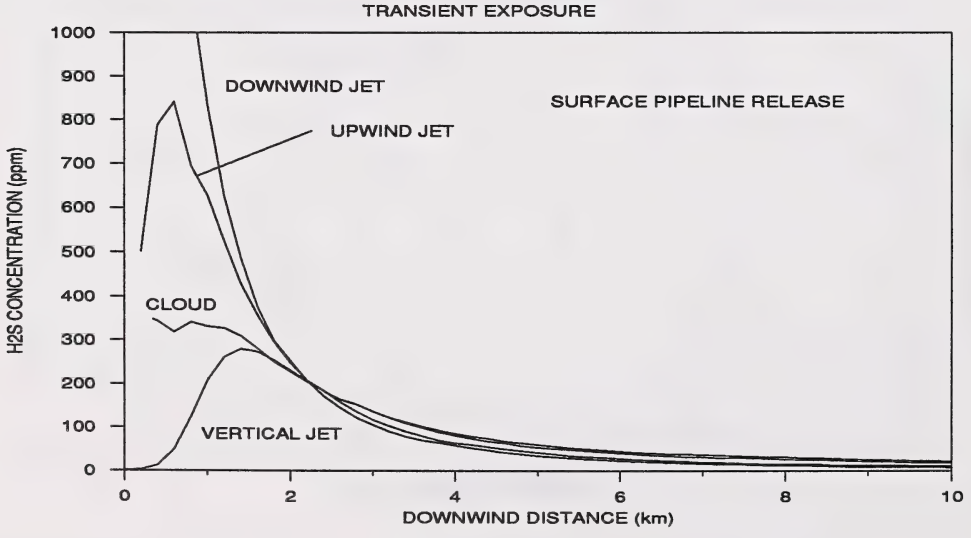

FIGURE 11

Predicted Peak H_2S Concentrations for Selected Surface Pipeline Rupture Geometries.

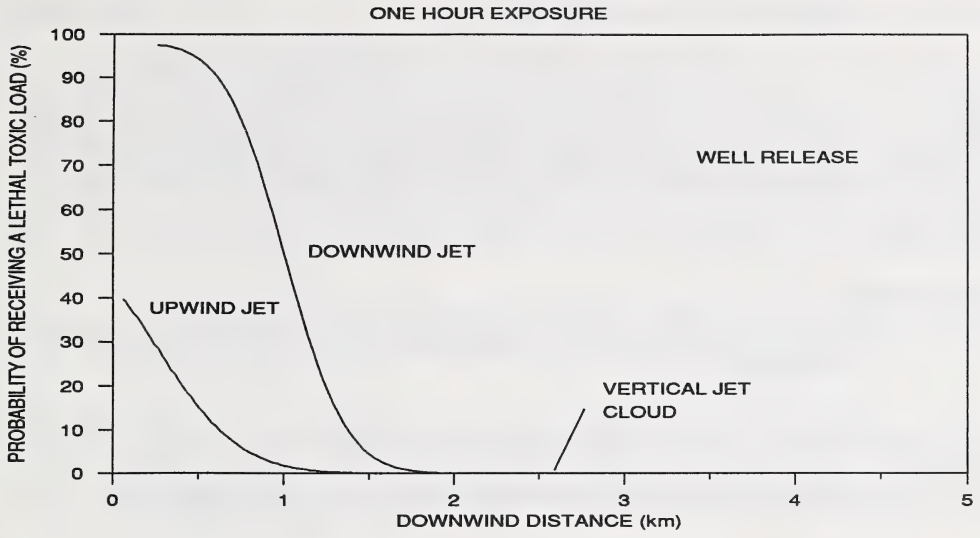

FIGURE 12

Predicted Lethality for Selected Well Geometry Scenarios.

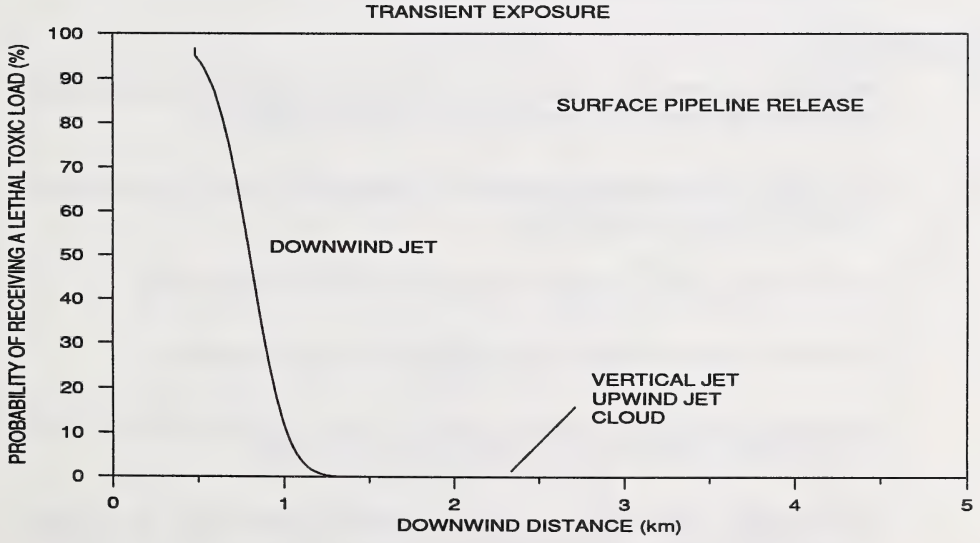

FIGURE 13

Predicted Lethality for Selected Pipeline Rupture Geometries.

7 Model Sensitivity Evaluation Results

Selected source and meteorological input parameters were varied within realistic limits to determine the impact on model predictions of ground-level H_2S and SO_2 concentrations and consequences due to H_2S for a wide range of release and meteorological scenarios. While a wide range of scenarios was considered, it is no doubt possible to conceptualize additional scenarios not addressed specifically in the sensitivity analyses section. For this reason, the following general observations from the model runs conducted to date should be viewed as preliminary:

Well Blowouts

- Horizontal jet releases result in the largest H_2S concentrations and highest consequences.
- Downwind jet releases produce larger concentrations than upwind jet releases.
- Vertical jet releases produce low concentrations due to high plume rise.
- Larger H_2S concentrations and consequences generally result from larger release rates for the unignited case.
- For the plume ignition case, the largest SO_2 concentrations near the well (within 20 km) are associated with smaller release rates.

Pipeline Ruptures

- Predicted concentrations and consequences do not appear to be sensitive to the location of the break in a pipeline segment (for long ruptures).
- The largest predicted concentrations and consequences result from the larger diameter, longer length pipelines.
- Downwind jet releases result in the largest predicted concentrations.
- Vertical jet releases result in the smallest predicted concentrations.
- Increased delay times for the ESD valves to isolate the pipeline segment result in the largest predicted concentrations and consequences.
- Full ruptures (100% hole size) give the highest concentration but a partial rupture of 50% area results in higher consequences due to the effect of exposure time.
- Concentrations and consequences due to buried pipe releases are very sensitive to emission angle. At angles greater than 20 ° from the horizontal, the downwind effects are negligible.

Meteorology

- Larger H_2S concentrations and consequences are predicted for smaller values of surface roughness.

- Maximum SO_2 concentrations are not sensitive to surface roughness, but the maximum occurs nearer to the well for larger values of surface roughness.

- Predicted concentrations are relatively insensitive to ambient temperatures.

- The largest predicted concentrations and consequences for horizontal releases occur under low wind speed, stable conditions (for unignited H_2S: 1 m/s and for ignited SO_2: 5 m/s).

- For neutral and unstable conditions, the highest predicted concentrations occur relatively close to the source and are associated with moderate to high wind speeds (3 to 15 m/s). Consequences are considerably less under these conditions compared to stable conditions.

In summary, the largest estimated exposure zones for unignited releases are associated with low wind speed stable atmospheric conditions with smooth terrain. For ignited releases, the largest estimated exposure zones are associated with moderate wind speed stable conditions with rough terrain.

8 Uncertainty in Model Predictions

Air quality dispersion model calculations contain uncertainties which can be classified as those arising from reducible errors and those arising from inherent uncertainties. Reducible errors result from errors in source and meteorological input data and from limitations in the model physics. Inherent uncertainties result from the random nature of atmospheric turbulent motions that are responsible for the transport and diffusion processes. To provide a confidence level on the model predictions, it is desirable to quantify these uncertainties. In the absence of observations to allow direct uncertainty analysis, this quantification will require subjective estimates.

Figure 14 shows the combined inherent and irreducible uncertainty for a selected well blowout H_2S release scenario. The band (± 38%) represents the smallest uncertainty which can be realistically expected for a given set of input parameters based on estimated uncertainties of these input parameters. This estimated uncertainty is similar to the magnitude of the uncertainties predicted by others and is as good as current technology permits. At first glance, the magnitude of the uncertainties associated with these type of model predictions may not be comforting. It should be kept in mind, however, that concentration values in the atmosphere can vary by many orders of magnitude and that a ± 50% uncertainty is better than not having any concentration estimates at all.

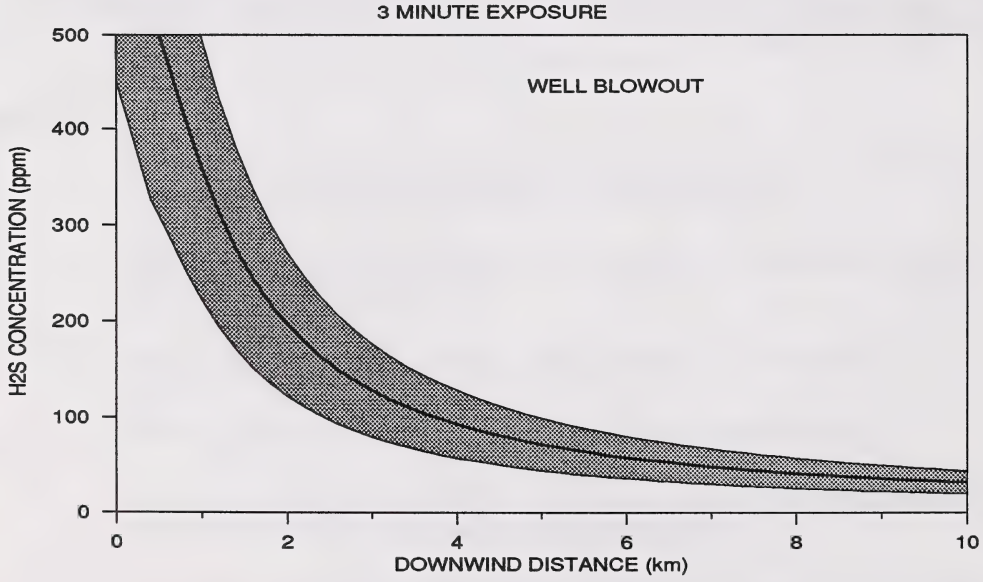

FIGURE 14

Estimated Uncertainty in the Prediction of H_2S Concentrations.

9 Model Comparison

Selected GASCON2 model formulations were compared with other formulations which have been used in Alberta. In particular, the following modules were evaluated:

9.1 Transient Release Rate

The double exponential blowdown model used by GASCON2 was compared to a more rigorous non-isentropic, non-ideal gas model to assess the capability of the former model to predict the high initial release rates.

The double-exponential model gives a somewhat higher release rate during the first 10 seconds following the rupture. It is during this period that the greatest departure from ideal gas behavior can be expected. Based on the comparison between the two models, it was judged acceptable to use the double-exponential model for dispersion modelling purposes.

9.2 Plume Rise

Ambient concentrations are sensitive to the height of the plume above the ground which is the sum of the source height and the plume rise. Final plume rise estimates from the GASCON2 model were compared to those obtained from the Briggs 1969 approach. Vertical unignited and ignited releases were assumed.

The predicted final plume rises for the unignited releases are dominated by the vertical momentum of the plume whereas the ignited releases are dominated by the buoyancy term. The predicted momentum dominated plume rises are generally much less than those which are dominated by buoyancy.

For unstable and neutral conditions, the predicted GASCON2 effective plume height for the portion of the plume which remains within the boundary layer is determined by the plume penetration criterion. These effective plume heights are much less than those predicted by using the Briggs 1969 approach for the complete plume at low wind speeds. At higher wind speeds the effective plume heights (plume rises) predicted by the two approaches are similar. For stable conditions, the predicted GASCON2 effective plume heights are similar but about 20% greater than the Briggs' 1969 approach.

9.3 Plume Spread

Predicted concentrations are also sensitive to the rate at which the plume spreads vertically and horizontally as it moves downwind. The GASCON2 plume spread values were compared to the Pasquill-Smith values used by Alberta Environment in their guideline dispersion models.

For unstable conditions, the use of the GASCON2 plume spreads are expected to produce ambient concentrations similar to, or larger than those associated with the use of the Pasquill-Smith plume spreads for moderate wind speeds of about 3 m/s. For lower wind speeds, the use of the GASCON2 plume spread values are expected to produce ambient concentrations smaller than those associated with the use of the Pasquill-Smith plume spreads.

For neutral conditions, the use of the GASCON2 plume spreads are expected to produce ambient concentrations larger than those associated with the use of the Pasquill-Smith plume spreads.

For stable conditions, the use of the GASCON2 model plume spreads are expected to produce ambient concentrations similar to, or larger than those associated with the use of the Pasquill-Smith plume spreads.

9.4 PLUMES2 Dispersion Model

The Alberta Environment model PLUMES2 was used to calculate H_2S and SO_2 concentrations which result from a vertical steady-state well release. The results were compared to those predicted by GASCON2 for stable atmospheric conditions:

For the unignited release scenario considered, it appears that GASCON2 is more conservative than PLUMES2. That is, GASCON2 predicts larger H_2S concentrations and larger potential hazard zones.

For the ignited release scenario considered, the peak SO_2 concentrations predicted by the models are sensitive to wind speed. For a 2 m/s wind, PLUMES2 predicts a higher peak concentration. For a 3 m/s wind, GASCON2 predicts a higher peak concentration.

9.5 PUFF Dispersion Model

The ERCB model is used to calculate H_2S concentrations which may result from a transient pipeline release. The results were compared to those predicted by GASCON2. Release-rate and plume-height profiles are required as input for PUFF and were obtained from GASCON2.

The downwind H_2S concentration profiles are similar for both models. The main differences occur near the release point. The similarity of the two profiles is not surprising since the GASCON2 release-rate and plume-height profiles were used as input into the PUFF model.

10 Comparison With Observations

Downwind H_2S and SO_2 concentrations are available from three publicized well blowouts in Alberta (Lodgepole, Claresholm and Rainbow Lake). GASCON2 model predictions were compared to observations associated with these blowouts. Due to the severe limitations of the data associated with each blowout, the comparison exercise should **NOT** be viewed as a model verification or validation exercise. The comparison exercise should only be viewed as providing a preliminary indication of the model performance.

Figure 15 compares model predictions with the observations. Mobile H_2S observations have been normalized to a three minute average while those from stationary monitors have been normalized to a one hour averaging period using the power law relationship. Stationary SO_2 observations were normalized from a one hour average to a three hour average.

The diagonal lines on the figure represent the perfect 1:1 correlation (perfect agreement) and the "factor of two" envelope. Predicted values are scattered both above and below the 1:1 line. Thirty-seven predicted values are above the 1:1 line (overprediction) and 12 predicted values are below the 1:1 line (underprediction) with one in perfect agreement.

In conclusion, the model appears (on the basis of limited data) to significantly overpredict for the downwind distances where observations were available (> 10 km).

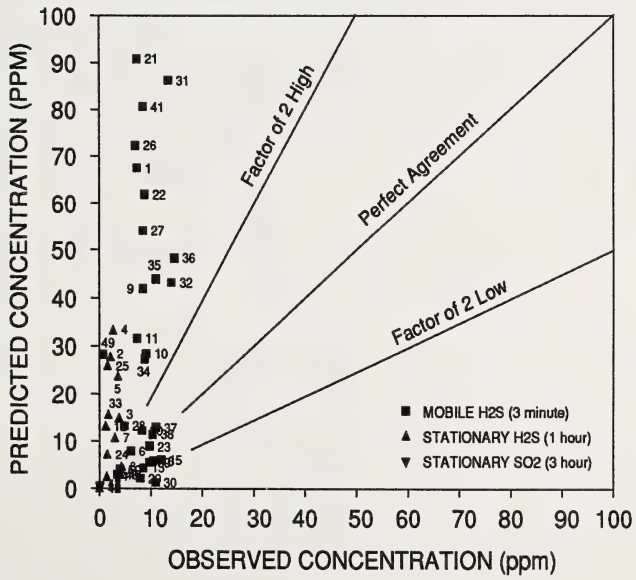

FIGURE 15

Predicted H_2S and SO_2 Concentrations for Selected Well Blowout Observations.

11 Conclusions

The GASCON2 model incorporates our current knowledge to produce an application-oriented model which can be used to estimate with more confidence than previously available models H_2S and SO_2 concentrations and consequences due to H_2S which result from uncontrolled sour gas releases . The model can be used as a tool to help ensure that public safety concerns in the vicinity of sour gas developments are addressed in a rigorous manner.

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ENVIRONMENTAL

Risk Approach

An Approach for Estimating Risk to Public Safety from Uncontrolled Sour Gas Releases

October 1990

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1 BACKGROUND

Implicit in the operation of sour gas facilities is the possibility of an accidental release of sour gas to the atmosphere. For example, during the 14-year period 1975 to 1988, five well blowouts occurred during the drilling of sour wells, seven blowouts occurred during sour gas production and seven occurred during non-production phases of operation. During the 14-year period 1975 to 1988, at least 30 ruptures were associated with sour gas pipelines. Due to the toxicity of H_2S, a large uncontrolled release upwind and close to a populated area could have serious consequences.

In the previous phase of this study, GASCON2, a **hazard** and **consequence assessment** model for uncontrolled sour gas releases, was developed. A hazard assessment is concerned with determining the consequences of an accidental release of sour gas.

Since a hazard assessment does not consider the causes of accidental events, it can not give a measure of how likely an accident is. If a hazard assessment is to be at all useful to emergency planners, it must give the hazards due to **worst case** scenarios, that is, accidental releases that give the largest ground level toxic gas concentrations, or the largest hazard zones. The trouble with worst case scenarios is that it is difficult to make planning decisions based on them alone. If people adopted worst cases as the basis for all of their decision-making, no action would ever be taken for fear of the possible outcomes. Almost any activity that would come to mind would be fraught with possible (but unlikely) consequences.

It is important to recognize that a worst case hazard alone cannot give a good measure of danger to the public; it must be viewed in terms of the likelihood of such a worst-case hazard occurring. When one speaks of the **likelihood**, or the **chances**, or the **probability** of an adverse consequence occurring, one is really referring to a concept called **risk**. Simply defined, risk is the likelihood that an adverse consequence will occur due to accidental events.

2 PROJECT OBJECTIVES

The overall objective of this project is the development of a simplified approach for estimating the risk to the public from potential uncontrolled sour gas releases. Risk depends on the consequence and frequency of events. The consequences of uncontrolled sour gas releases are estimated using GASCON2 (Alp *et al.* 1990). This report documents the approach to obtain the frequencies and provides the historical frequency of uncontrolled sour gas releases in Alberta.

More specifically, the objective of this phase of the study is to develop a risk assessment method, consisting of a frequency analysis approach and a computer-based consequence assessment model, which can be used as a practical tool for estimating the risk to the public posed by accidental sour gas releases. The steps were:

- To review the literature to establish what is the current knowledge on frequency analysis applied to uncontrolled sour gas releases,

- To evaluate historical data to determine the frequency of uncontrolled sour gas releases,

- To incorporate these results, along with the GASCON2 hazard and consequence assessment model, into a risk assessment approach, and

- To apply the approach to the various generic worst-case conditions.

The project described in the report was done under contract to the Energy Resources Conservation Board (ERCB) by Concord Environmental Corporation. A Scientific Advisory Board appointed by the ERCB provided peer review to assure the technical acceptability of the overall approach.

3 RISK ASSESSMENT METHOD

Risk is an inseparable part of everyone's life. Every person lives with the knowledge that an unexpected event can intervene at any time in their life, and that some events are more likely to happen (i.e. riskier) than others. The less risk posed to us by accidental events, the safer we are. Therefore, risk, which is a quantifiable number (e.g. 1 chance in a million, or a probability of 0.000001), is an objective measure of how safe people are from accidental events.

Consideration of risk is preferable to worst case scenarios for emergency planning purposes. With a risk assessment, it is possible to examine various safety measures and see how significantly they reduce the risk. This is often termed "**looking at mitigative measures**". When risk numbers, along with costs, benefits and mitigating measures enter into the decision-making of emergency planners, the process is often called **risk management**.

The relationship between hazard assessment and risk assessment is shown schematically in Figure 1. Risk assessments are divided into two main parts: the **frequency analysis** and the **consequence analysis**. The main component of the consequence analysis is the detrimental effects modelling, which estimates the adverse effects of the toxic gas concentrations given by the hazard assessment. The frequency analysis part of the risk assessment deals with estimating how likely an accidental release of sour gas is. The main component of frequency analysis is a tool called **fault tree analysis**, which is the development of a diagram showing the chain of sub-events that must occur for an accidental release of sour gas to happen.

In this study, an accidental sour gas release is termed an **uncontrolled sour gas release event**, or simply **event**, for short.

Consequence analysis answers four questions for a given event:

- *What is the concentration of H_2S at locations downwind of a release point?*

- *How large is the hazard zone where H_2S concentrations exceed a criteria level?*

- *What is the probability of receiving a lethal toxic load (dose) of H_2S at locations downwind of a release point?*

- *How many potential fatalities could occur if there were people outdoors during the release?*

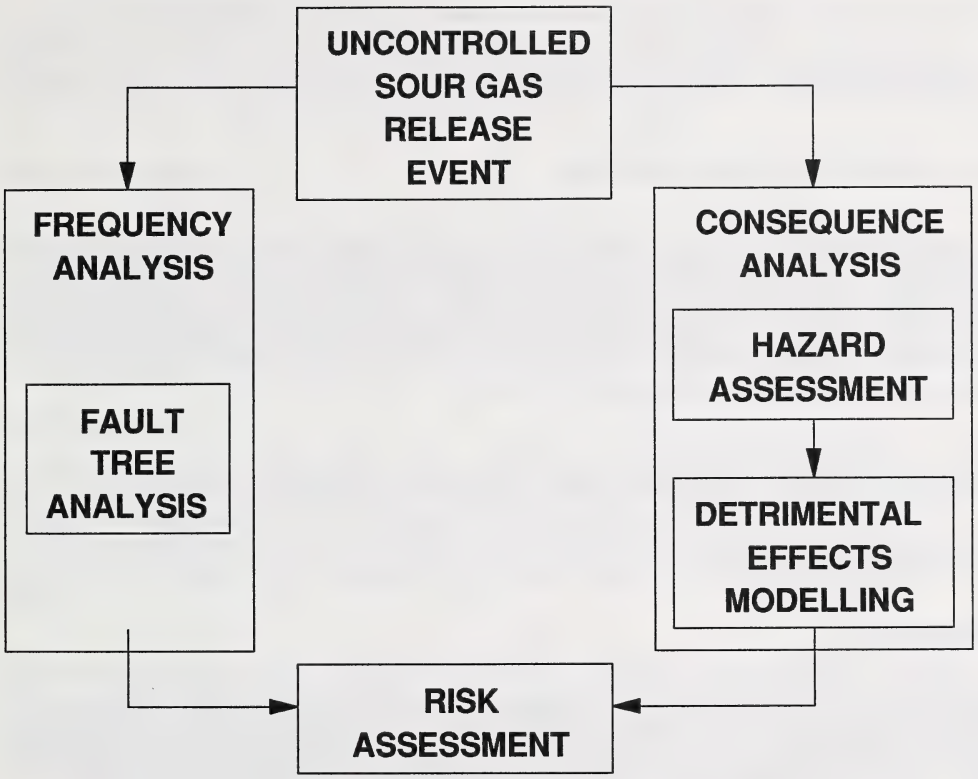


Figure 1

General Risk Assessment Elements.

The frequency analysis answers the questions:

"What are the chances of an event occurring?"

Mathematically speaking, risk is the frequency of an event times the consequence of an event.

Two kinds of risk numbers come out of the risk assessment: **individual risk** and **societal risk**. In this study, individual risk is taken to mean the likelihood or probability that a person will receive a lethal exposure to H_2S due to an accidental release. This likelihood will change from one downwind location to another, and from one kind of accidental release to another. Societal risk is an estimate of the potential number of fatalities which could result from an accidental sour gas release. This may be viewed as the sum of the individual risks of all the people in the area to the sour gas release. Again, the societal risk will change from one kind of accidental release to another.

The approach described in this report determines **incident risk** for a given uncontrolled sour gas release event. **Facility risk** is the sum of the incident risks for all of the possible uncontrolled sour gas release events. In practice, worst case events are selected to represent the possible events.

4 CONSEQUENCES ANALYSIS

An event is defined by a unique combination of sour gas **release conditions** and **weather conditions**. The event results in ground level toxic gas concentrations which vary with distance from the release point and, hence, also results in varying potential for fatal exposures to toxic gas. There are a number of factors which define the release conditions and weather conditions, and hence an event. In addition to these, **detrimental effects factors** are also required to estimate the consequences of an event.

These release and weather conditions that define an event and the detrimental effects factors, which are inputs to the GASCON2 model, will now be described in some detail.

4.1 Release Conditions

Well Blowouts

A well blowout is characterized by a continuous release rate of sour gas until the well is brought under control. The duration of the release can typically be days or even weeks, although ignition of the sour gas can take place in a matter of minutes or hours. The rate at which sour gas escapes from the well (called the release rate) is either known for producing wells, or can be estimated from the release rates of nearby wells in the same geological formation for proposed wells. Figure 2 shows the types of uncontrolled well flows considered.

Pipeline Ruptures

In contrast to well blowouts, pipeline ruptures typically last in the order of minutes rather than hours or days. At the moment of rupture, the flow rate of escaping gas is high. Since the ruptured section of pipeline is isolated by Emergency Shutdown Valves (ESD) from the wells and the rest of the pipeline system, the line pressure and flow rate decrease as the isolated section of pipeline is depleted of sour gas. The model is capable of predicting the flow rate of sour gas through a pipeline rupture opening, given the following:

- Area of the rupture opening.
- Internal diameter of the pipeline.
- Length of pipeline which is being depleted.
- Line pressure in the pipeline before rupture.
- Line temperature in the pipeline before rupture.

- Sour gas composition.

The above factors are known from pipeline operating conditions or can be estimated. Figure 3 shows the kind of pipeline ruptures that have been considered.

Flow Orientation

Should a well blowout or pipeline rupture occur, the escaping gas would not necessarily be an upward directed jet of sour gas. A pipeline rupture can occur anywhere along the circumference of the pipeline. The flow from a well blowout can be re-directed or slowed down by obstacles to the flow, or can be directed horizontally by valve fittings. Figures 4 and 5 show the flow orientation considered for both well blowouts and pipeline ruptures.

Gas Composition

The amount of hydrogen sulphide (H_2S) in the sour gas is important in determining what the H_2S concentration would be downwind of an accidental release. This can vary considerably from one gas pool to another. The constituents of sour gas are either known for producing wells or can be estimated from nearby wells in the same pool for proposed wells.

All the constituents of the sour gas (for example, methane, hydrogen sulphide, propane, ethane, carbon dioxide, nitrogen, etc.) are important in estimating the properties of sour gas and in estimating what happens when the gas is ignited. Perhaps the most important property of sour gas to be determined is its **density**, which normally is somewhat less than that of air, and which affects the buoyant rise of the sour gas plume in the atmosphere.

Ignited or Unignited

The ignition of a sour gas release can be either by design or by accident. For ignited releases, the toxic material of concern is sulphide dioxide (SO_2), whereas for unignited releases, the toxic material of concern is hydrogen sulphide (H_2S). Ignition causes a significant rise in the temperature of the released material, making it rise further in the atmosphere. Consequence analysis is only done for unignited releases because H_2S concentrations are higher and H_2S is more toxic.

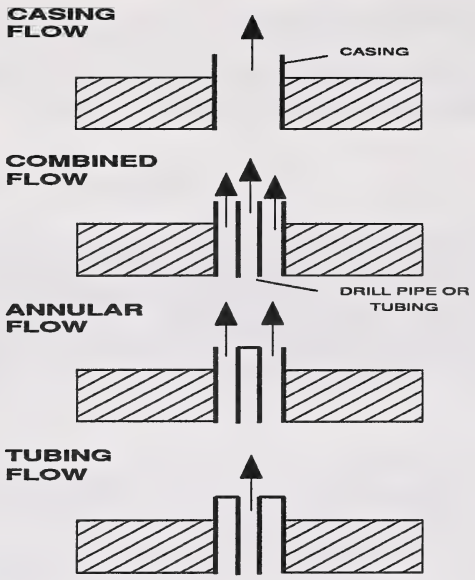


Figure 2

Possible Well Flow Scenarios.

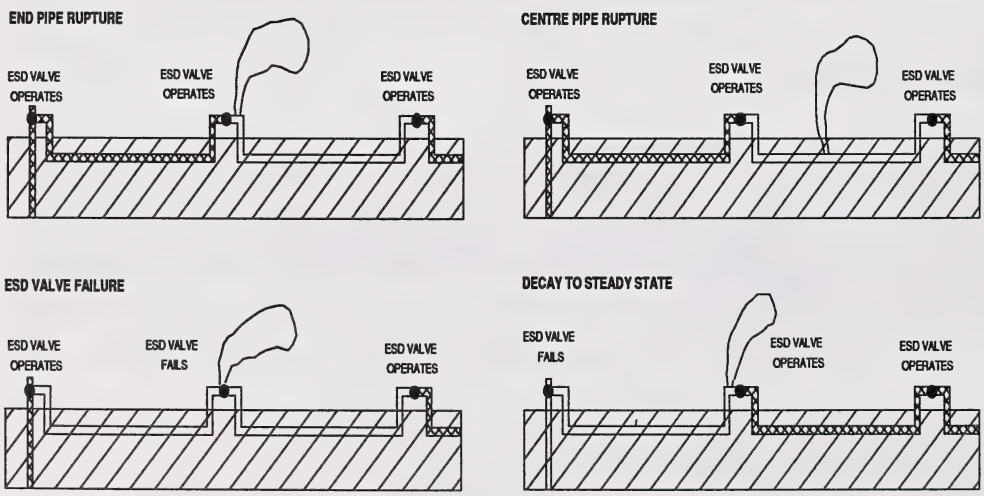


Figure 3

Possible Pipeline Rupture Scenarios.

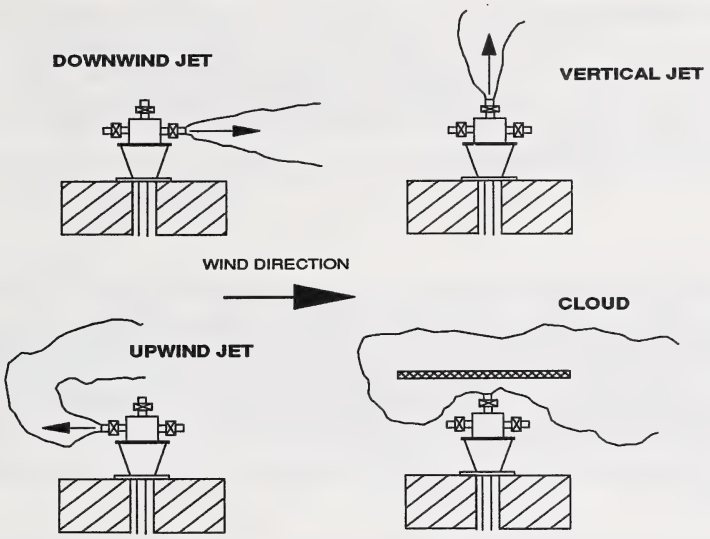


Figure 4

Possible Well Release Geometries.

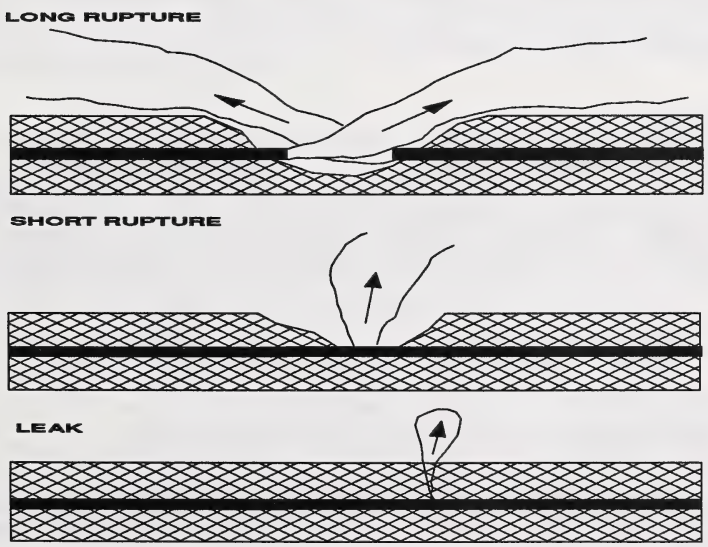


Figure 5

Possible Pipeline Release Geometries.

4.2 Weather Conditions

Weather conditions determine the ability of the atmosphere to transport and dilute the sour gas from an accidental release. The following are the weather factors that determine the dispersing capability of the atmosphere.

Wind Speed

Wind speed directly affects the transport of toxic gases in the atmosphere by determining the distance the material moves in a given period of time and the dilution of the material in the along-wind direction. Indirectly, wind speed also affects the rise of the sour gas plume (the faster the wind speed, the lower the plume rise) and the level of turbulence in the atmosphere (the faster the wind speed, the greater the level of turbulence). Increased turbulence levels will increase the dilution of the plume.

Wind Direction

Wind direction determines the direction in which sour gas will be carried and dispersed and the geographical area which will be exposed to the toxic gas.

Temperature

At colder outdoor temperatures, the ambient air becomes more dense relative to the sour gas. Because the sour gas is more buoyant in these situations, it will tend to rise higher. The converse is true for warmer temperatures.

Surface Roughness

Surface roughness is a site-dependent factor which depends on the presence of terrain features such as trees, buildings and crops. An increase in surface roughness will increase the dilution of toxic gas releases. Surface roughness factors are tabulated in many meteorological reference texts under qualitative descriptions of various terrain types.

Stability

Atmospheric stability refers to the level of turbulence in the lowest level of the atmosphere, known as the Planetary Boundary Layer (PBL), within which we live.

- **Unstable** conditions occur when there is significant solar heating of the ground, as one might expect during sunny daytime hours in summer. Under these conditions, large scale convective motions in the form of updrafts and downdrafts are set up in the PBL, causing the rapid dilution of toxic material.

- **Stable** conditions occur when there is cooling of the ground by radiation, as one might expect during the night. Turbulent motions are suppressed in the PBL and toxic gas disperses slowly in these conditions.

- **Neutral** conditions occur when turbulence is neither enhanced (as in unstable conditions) nor suppressed (as in stable conditions). Neutral conditions can occur during transition periods between stable and unstable and vice versa. They can also occur under high wind conditions.

Atmospheric stability is not a routinely measured parameter, and must be inferred from other routine weather observations.

Mixed Layer Height

This is essentially the height of the PBL in which turbulent mixing takes place. Due to strongly suppressed levels of turbulence at the top of the mixed layer and possible temperature inversions, the mixed layer height can often act as a lid, restricting vertical movement of sour gas plume. This can reduce the dilution properties of the atmosphere. On the other hand, a plume which has enough upward momentum to penetrate partially through the mixed layer reduces the amount of toxic gas material to be dispersed within the mixed layer.

The mixed layer height is typically greatest in unstable conditions, when it can be as high as 1500 to 2000 metres. The mixed layer height is typically lowest in low wind speed stable conditions, when it can be as low as 50 to 100 metres.

The mixed layer height is not a routinely measured factor and must be inferred from other observations.

4.3 Detrimental Effect Factors

This section really accounts for two very important factors in the determination of the detrimental effects to people due to an accidental sour gas release. The first factor is the variation in toxic gas concentration ("fluctuating load") due to the natural turbulence in the atmosphere. The second factor is the human vulnerability to toxic gas exposure ("probit analysis"). Together these two factors give an estimate of the likelihood that people exposed to sour gas during an accidental release would be adversely affected. The following parameters determine the consequences of an accidental sour gas release.

Exposure Time

If a sour gas well blowout were to occur, the toxic effect of H_2S would depend on the length of time people would be exposed to the toxic gas. This exposure time would strongly depend on the delay time for ignition of the sour gas release from a well blowout or the time to deplete a ruptured pipeline segment.

Human Vulnerability to Toxic Gas

Experiments performed on animals and limited documented incidents of accidental human exposures to toxic gas have indicated that both concentration level **and** exposure time are important in defining the potential for an adverse effect. This potential is called the **toxic load**. The toxic load is similar to the concept of **dose**, in that the greater the toxic load that

a person is exposed to, the greater his chances of responding adversely. An increase in **either** toxic gas concentration **or** exposure time will increase the toxic load, however the toxic load is more dependent on changes in concentration than exposure time.

The toxic load concept, and its implementation in human susceptibility modelling, is a large step forward in consequence assessment methodology. Whereas previous work has made extensive use of critical concentration levels, and the hazard zones defined by them, the approach used in GASCON2 accounts for exposure time effects in a realistic way using the toxic load concept.

Variation in Toxic Gas Concentration

Peak concentrations may be several times the average concentration due to the natural turbulent motions of air in the atmosphere. Toxic loads based on average concentrations are not adequate to model adverse effects since the periods of peak concentrations would be severely understated.

The GASCON2 model incorporates a current model for concentration variability in its treatment of detrimental effects. The model is capable of accounting for the peak periods in toxic gas concentration because human vulnerability is modelled as exposure time and H_2S concentration dependent.

Population Density

The potential number of people that can be adversely affected by an accidental sour gas release is dependent on the population density (people per square kilometre) in the exposure zone around a sour gas facility.

5 Frequency Analysis

Frequency analysis is concerned with estimating the likelihood of an accidental sour gas release. This likelihood is expressed as a **frequency** of occurrence of an accident in units of accident events per year. For example, an accident that is estimated to have a frequency of occurrence of 0.00001 accident events per year is equivalent to a frequency of occurrence of 1 accident event every 100,000 years.

The tool used to estimate the frequency of occurrence of an accident is fault tree analysis. This technique focuses on one particular accident event and uses a logical method for determining potential causes and probabilities of the event occurring.

An example of a fault tree can be seen in Figure 6. In this simplified example, an automobile accident is explored for possible causes. In the figure, an automobile accident is assumed to result from **either** a brake failure **or** driver error. A more complete fault tree might consider other causes as well, such as the failure of other equipment. In the example, a brake failure can be caused by **either** inadequate maintenance **or** a faulty brake component. A faulty brake component requires **both** a manufacturing error **and** a factory inspection error.

By assigning or estimating the likelihood of the various sub-events occurring near the bottom of the fault tree (e.g., factory inspection error, improper maintenance in Figure 6), it is possible to follow the fault tree to the top-event (i.e., automobile accident in Figure 6) and estimate a likelihood that it will occur.

In the case of accidental sour gas releases, fault trees were developed for:

- Drilling of wells,
- Non-drilling phase of wells, and
- Pipelines.

The non-drilling phase of wells include producing, suspended, capped, standing, gas injection and storage wells.

The top event in these fault trees is a sour gas release for a given release condition and weather condition. In other words, the occurrence of specific release conditions and weather conditions are sub-events in the fault trees. The probability of these sub-events determine the frequency of the given event. The frequency of the hazard F_H (events/year) must be multiplied by the following probabilities to determine the frequency of an event:

- P_I - probability of non-ignition,
- P_E - probability of a potential emission rate,
- P_G - probability of a potential geometry,
- P_M - probability of a potential meteorology,
- P_θ - probability of winds blowing release from source to receptor during potential meteorology being considered, and
- P_R - probability of receptor being outdoors during exposure.

The various sources of data used in estimating the frequencies were:

- Historical observations of well blowouts and pipeline ruptures in Alberta,
- Historical equipment failure data,
- Engineering reliability calculations,
- Engineering judgement, and
- Meteorological observations.

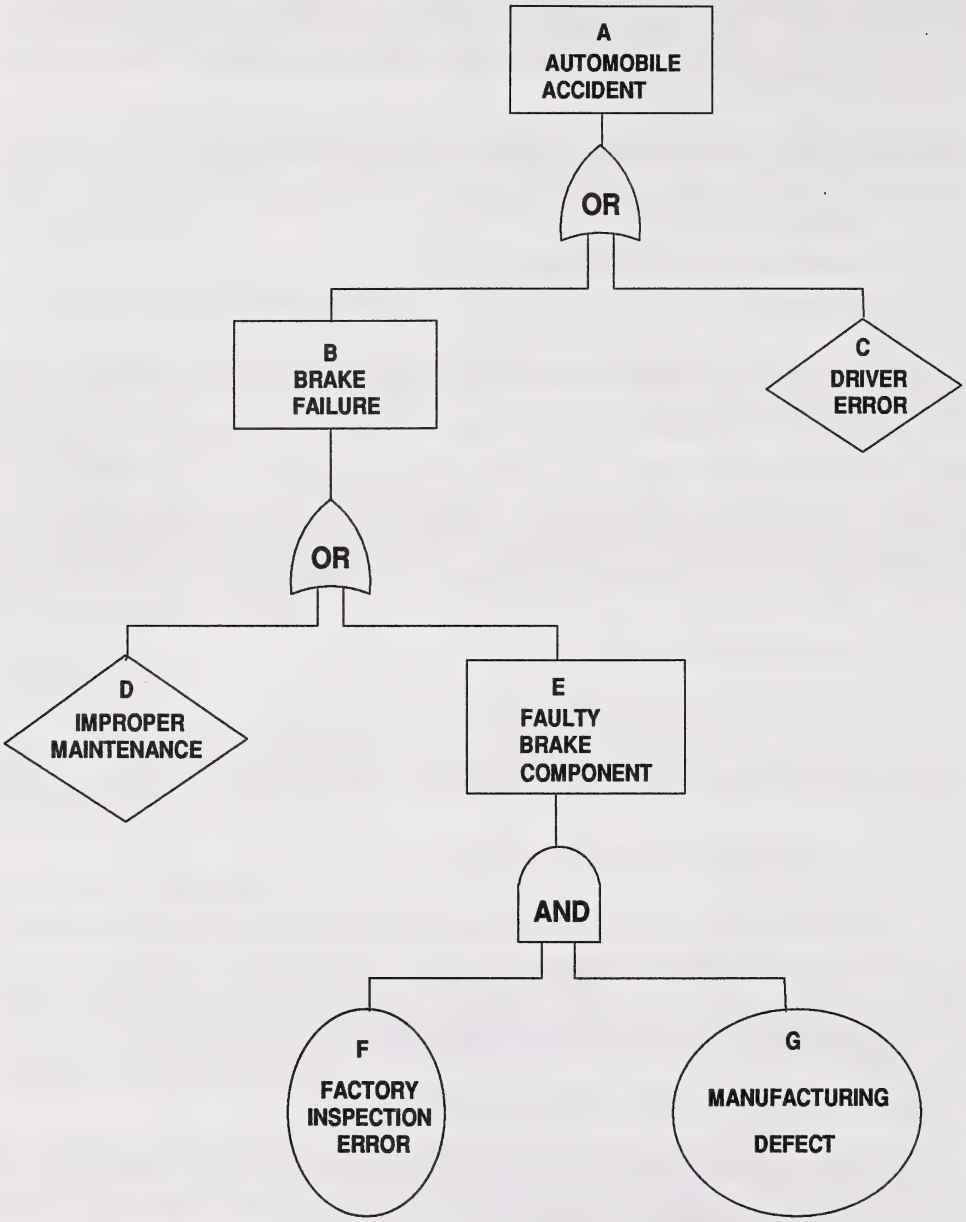


Figure 6

Example of a Fault Tree.

Table 1 summarizes the base case frequency analysis for the given events. The same base cases that were used in GASCON2 appear in the table. The drilling case is for a well flowing up the drill pipe with a downwind jet. The non-drilling cases are for producing and non-producing (suspended, capped and abandoned) wells. They reflect a flow up the tubing with a downwind jet. The pipeline cases are for both ruptures and leaks. The pipeline rupture case is categorized by the flow scenarios outlined in GASCON2.

A sensitivity is done on the base case to arrive at a high and low estimate. These numbers indicate that the frequencies are relatively low for all cases except pipeline leaks, which have less potential for adverse consequences.

Table 1

Frequency Analysis Results.

System	Description	Units	Base Frequency	High Estimate	Low Estimate
Drilling Well	Base Case (Drill Pipe Flow)	Number/Well Drilled	$2.53 \cdot 10^{-9}$ (1 in 370 million)	$1.16 \cdot 10^{-7}$ (1 in 8.6 million)	$5.20 \cdot 10^{-10}$ (1 in 1.9 billion)
Producing Well	Base Case (Tubing Flow)	Number/(Well•year)	$1.32 \cdot 10^{-7}$ (1 in 7.5 million)	$2.01 \cdot 10^{-6}$ (1 in 497 thousand)	$5.21 \cdot 10^{-8}$ (1 in 19 million)
Non-Producing Well	Base Case (Tubing Flow)	Number/(Well•year)	$2.20 \cdot 10^{-8}$ (1 in 45 million)	$2.23 \cdot 10^{-7}$ (1 in 4.5 million)	$9.70 \cdot 10^{-9}$ (1 in 102 million)
Pipeline Ruptures	End Pipe Rupture	Number/(km•year)	$3.63 \cdot 10^{-7}$ (1 in 2.8 million)	$1.52 \cdot 10^{-6}$ (1 in 0.6 million)	$8.00 \cdot 10^{-9}$ (1 in 125 million)
	ESD Valve Rupture	Number/(km•year)	$2.00 \cdot 10^{-9}$ (1 in 500 million)	$1.70 \cdot 10^{-8}$ (1 in 59 million)	$3.37 \cdot 10^{-11}$ (1 in 29 billion)
	Centre Pipe Rupture	Number/(km•year)	$4.13 \cdot 10^{-6}$ (1 in 242 thousand)	$4.52 \cdot 10^{-6}$ (1 in 221 thousand)	$1.03 \cdot 10^{-7}$ (1 in 9.7 million)
	Decay to Steady State	Number/(km•year)	$5.30 \cdot 10^{-8}$ (1 in 18.8 million)	$1.08 \cdot 10^{-7}$ (1 in 9.3 million)	$6.0 \cdot 10^{-9}$ (1 in 166 million)
Pipeline Leaks	Centre Leak	Number/(km•year)	$1.48 \cdot 10^{-4}$ (1 in 6.7 thousand)	$2.69 \cdot 10^{-4}$ (1 in 3.7 thousand)	$6.88 \cdot 10^{-5}$ (1 in 14.5 thousand)

Note: All values refer to an uncontrolled sour gas release for a given probability of non-ignition (P_I), emission rate (P_E), source geometry (P_G) and meteorological condition (P_M).

6 RISK EXAMPLES

The GASCON2 modelling system and the proposed method were used in assessing risks to the public from typical sour gas facilities and for assessing the usefulness of design changes in terms of their impact on safety. Concentration, consequences and risk results are presented for the following scenarios:

Well Parameters

- AOF sour gas release rate of $1000 \cdot 10^3$ m^3/d at sand face.
- Tubing release diameter of 53.4 mm.
- Casing release diameter of 156.3 mm.
- H_2S concentration of 30% in the sour gas.
- Producing operations result in tubing flow.
- Drilling and servicing operations result in casing flow.
- Horizontal jets assumed.

Pipeline Parameters

- Total pipeline length of 6000 m, consisting of one segment or 2 equal segments.
- Pipeline diameter of 254.4 mm.
- Rupture area equivalent to 100% of pipeline area.
- Leak area equivalent to 1% of pipeline area.
- H_2S concentrations of 30% in sour gas.
- Horizontal jet releases from surface pipe associated with ESD valve.
- Cloud releases at 10° to horizontal for buried pipe releases.

Atmospheric Parameters

- Stable atmospheric conditions.
- Wind speed of 1 m/s and a mixing height of 28 m.
- Flat or gently rolling terrain covered by mature agricultural crops.
- Frequency based on observations at Calgary International Airport.
- Winds from west.

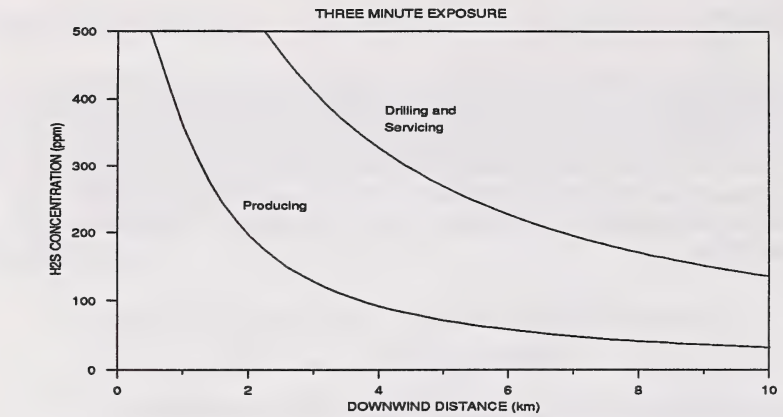
Well Blowout Predictions

Table 2 gives the frequency and the societal risk and Figure 7 gives the concentration, consequences and individual risk of the events modelled. The concentration and consequence for drilling and servicing operation are the same. However, the frequency of blowouts during servicing is higher than for drilling, so the risk is greater. The producing phase of operation has the lowest risk. Societal risk for production operations is considerably less as the number of people exposed to the release is less, since lethal concentrations do not extend as far downwind.

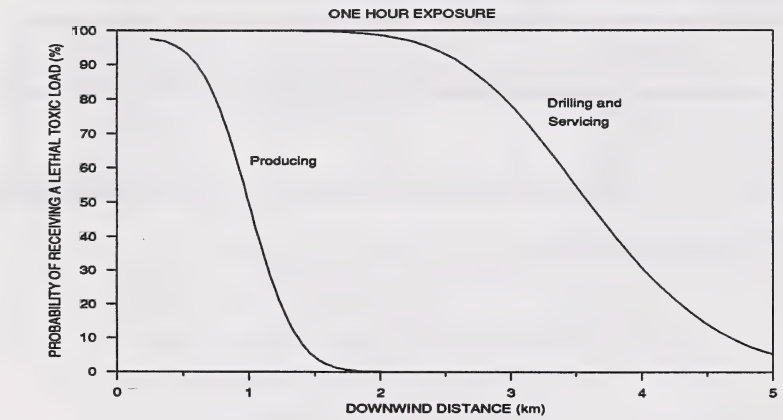
Table 2

Frequency and Societal Risk for Selected Well Blowout Scenarios.

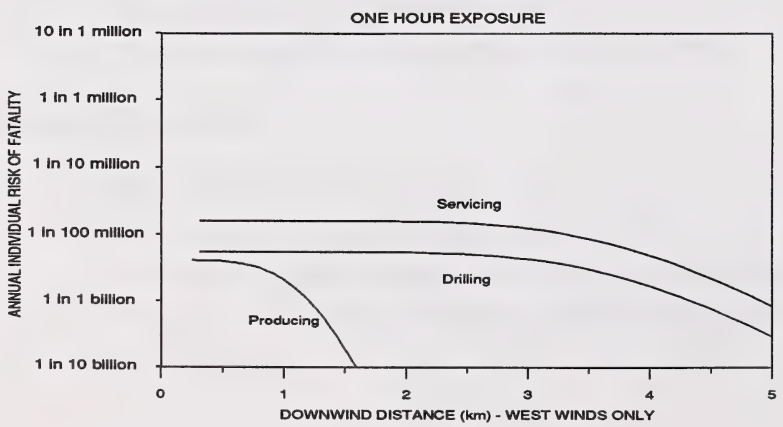
	Frequency (events/year)	Consequences (fatalities/event)	Societal Risk (fatalities/year)
Drilling	$5.6 \cdot 10^{-9}$	37	$2.1 \cdot 10^{-7}$
Producing	$4.2 \cdot 10^{-9}$	5	$2.1 \cdot 10^{-8}$
Servicing	$1.6 \cdot 10^{-8}$	37	$5.9 \cdot 10^{-7}$



Concentration (Note x-scale change from graphs below)



Consequence



Risk

Figure 7

Predicted H_2S Concentrations, Probability of Lethality and Risk of Fatality for Selected Well Blowout Scenarios.

Pipeline Leaks and Ruptures

Table 3 gives the frequency and societal risk and Figure 8 gives the concentration, consequences and individual risk of the events modelled.

The 6 km buried pipeline results in the highest H_2S concentrations and consequences; however, leaks from buried pipelines result in zero predicted probability of receiving a lethal toxic load and zero potential fatalities.

The 3 km buried pipeline has lower concentrations and thus lower consequences than the 6 km buried release and the 3 km surface release. Note that the frequency for the two 3 km buried sections is the same as for the 6 km buried section.

The leak from surface pipe results in an exposure zone which extends 1 km downwind and results in 0.03 potential fatalities. Leaks have the highest frequency but lowest consequences, thus their contribution to risk is low.

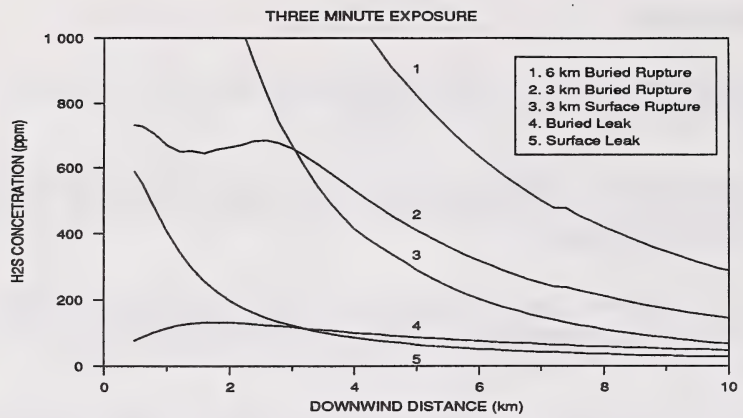
To determine the system risk, the risk from each release type from each component of the system must be added. For the scenario without the valve, risk is the sum of the risk due to leaks and ruptures. Similarly, when the valve is considered, the contribution to risk from leaks and ruptures in each of the 3 km buried sections and in the surface pipe are added.

For the pipeline parameters modelled, the installation of an additional ESD valve reduces the societal risk by about a factor of 18 and the maximum individual risk by about a factor of 2.

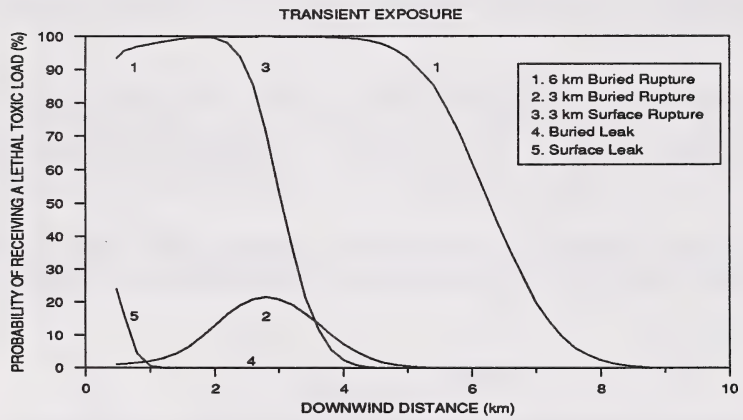
Table 3

Frequency and Societal Risk for Selected Pipeline Leak and Rupture Scenarios.

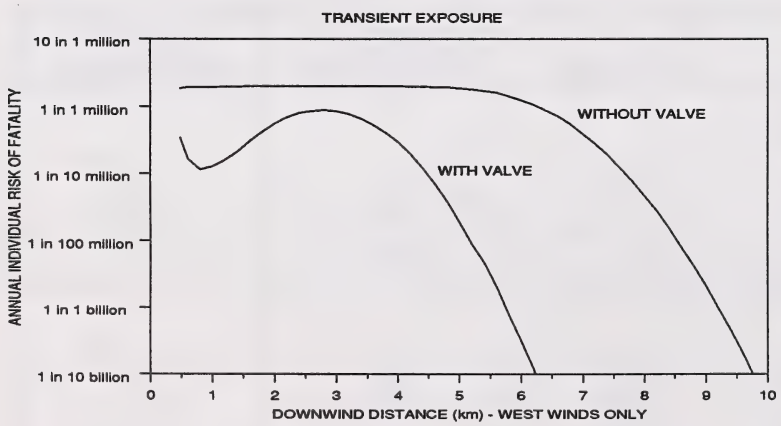
	Frequency (events/year)	Consequences (fatalities/event)	Societal Risk (fatalities/year)
Before No ESD Valve			
Buried Leaks	$8.3 \cdot 10^{-4}$	0.0	0.0
Buried Ruptures	$1.3 \cdot 10^{-5}$	31	$4.1 \cdot 10^{-4}$
Total	N/A	N/A	$4.1 \cdot 10^{-4}$
After With ESD Valve			
Buried Leaks	$8.3 \cdot 10^{-4}$	0.0	0.0
Surface Leaks	$1.1 \cdot 10^{-5}$	0.03	$2.9 \cdot 10^{-7}$
Buried Ruptures	$1.3 \cdot 10^{-5}$	1.4	$1.9 \cdot 10^{-5}$
Surface Ruptures	$2.9 \cdot 10^{-7}$	14	$4.1 \cdot 10^{-6}$
Total	N/A	N/A	$2.3 \cdot 10^{-5}$



Concentration



Consequence



Risk

Figure 8

Predicted H_2S Concentrations, Probability of Lethality and Risk of Fatality for Selected Pipeline Leak and Rupture Scenarios.

7 CONCLUDING REMARKS

A method has been developed to estimate individual and societal risk for an incident. The two key inputs are:

(i) the consequences of a sour gas release event from uncontrolled well blowouts or pipeline ruptures (from the GASCON2 model) and,

(ii) the expected frequencies of such events.

In practical applications, the degree of risk reduction possible as estimated by GASCON2 for the various alternative designs for a facility can be weighed against the cost of the various designs so that informed risk management decisions can be made. In such decisions at least one other factor, apart from the risk and cost factors, must also be considered. This factor consists of the socio-political considerations, which include value judgements as to the acceptability of a given level of risk. This requires input from the public.

ERCB Report 90-B
Volume 7

ERCB

Risk Approach

An Approach for Estimating Risk to Public Safety from Uncontrolled Sour Gas Releases

ERCB Supplemental Appendices to Volumes 5 and 6

October 1990

Risk Approach
Volume 7

Volume 7 contains Appendices A to D for Volumes 5 and 6. Appendix A is a compilation of data from various departments within the ERCB. The data was used to determine frequency of occurrences for events that could lead to a sour gas release as well as the frequency of a sour gas release itself. Appendix B is a paper by Bob Rogers on the triple shifted Rijnomd equation. Appendices C and D are papers by Dave Wilson on fluctuating concentrations and effective turbulence velocities, respectively. Pages 7 to 18 contain samples of the data found in Volume 7.

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ACKNOWLEDGMENTS

There are two groups of people that deserve recognition for assisting Concord Environmental Corporation in its assessment of the risk posed from an uncontrolled release of sour gas. They are the ERCB staff and the Scientific Advisory Board. The many extra hours of effort these people contributed are greatly appreciated:

The ERCB Staff

The project co-ordinator **Lynda Holizki** who was assisted by many staff members:

From the Environment Protection Department **Jim Davis** who co-ordinated the data collection on well blowout and pipeline statistics and assisted Concord by developing spread sheets to handle the fault tree analysis.

John Sutherland who spent many hours generating graphs for this document.

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From the Drilling and Production Department **Bill Wylie** who provided both data and first hand knowledge on well blowouts. Bill presented a paper on well blowout and kick information at the 1990 SPE conference. Bill's work in this area was of valuable assistance.

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Hal Knox who provided advice at the early stages of the work.

From the Gas Department **Harvey Halladay** who by understanding the ERCB data base and the issues of sour gas moved our understanding of the sour gas statistics significantly forward and improved the reliability of the sweet/sour data splits substantially.

Ian Dowsett who assisted by generating graphical representation of the sour gas data.

Andy Warren who contributed his recent work on shallow gas reserves in the Southeastern Alberta area.

From the Pipeline Department **Alan Cassley, Gary Ziehr** and **Andrea Larson** who provided both pipeline rupture data and advice on the use of that data.

Roger Creasey (formerly from the Pipeline Department) who initially reviewed the rupture data and provided advice to Concord on its fault tree analysis.

The Scientific Advisory Board

Members of the Scientific Advisory Board were asked to sit on the Board for the expertise they brought to bear on the issues at hand. In some areas their own research provided the necessary science for Concord to develop the GASCON/GASRISK model. The backup documentation for this science is contained in this document. There are two technical papers by **David Wilson** and one by **Bob Rogers**. The ERCB wishes to acknowledge these contributions and to thank both of these individuals for allowing the ERCB to include them here.

NUMBER OF PRODUCING GAS POOLS BY SWEET/SOUR SPLIT

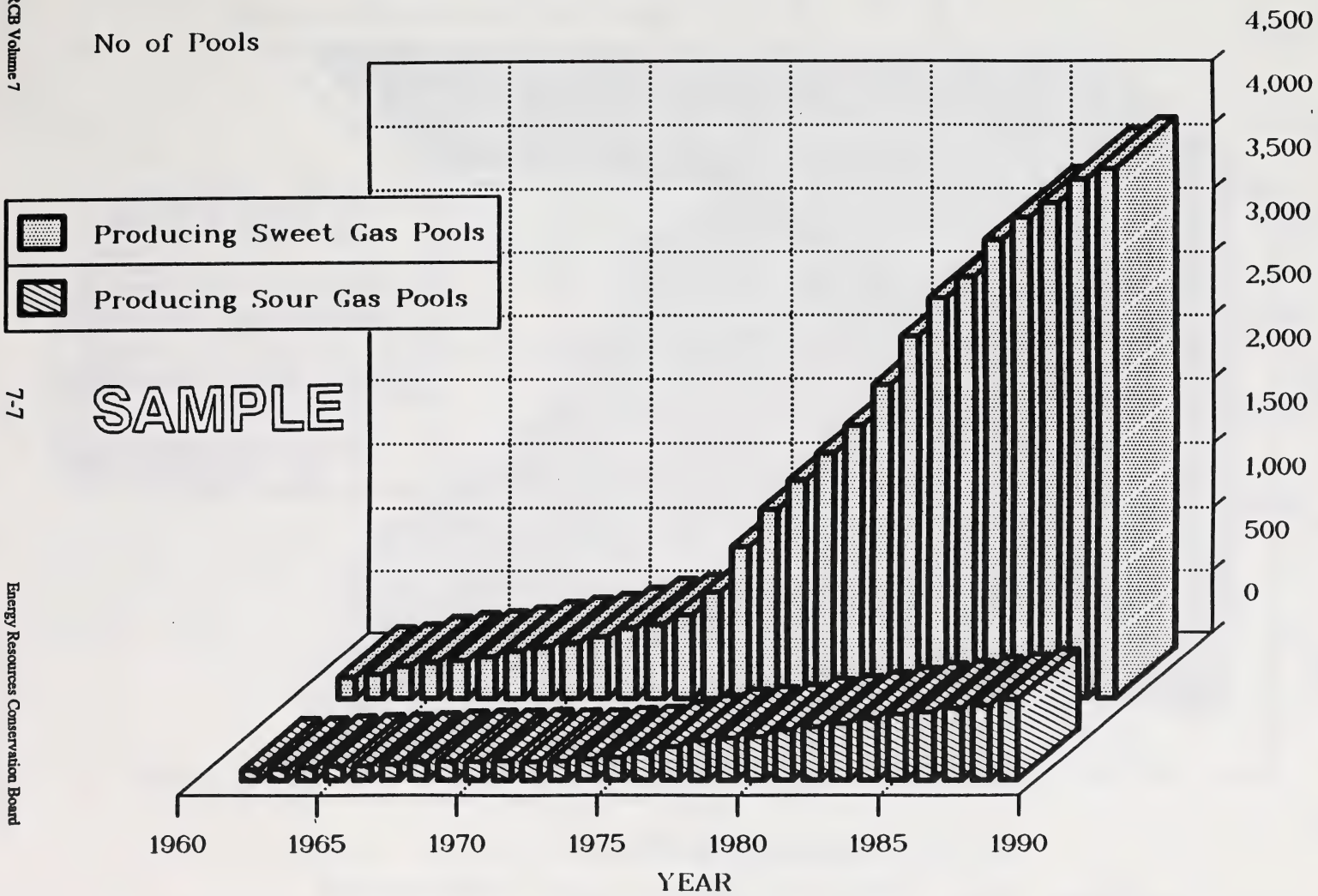


FIGURE 3.1

Number of Producing Gas Wells by Sweet/Sour Split

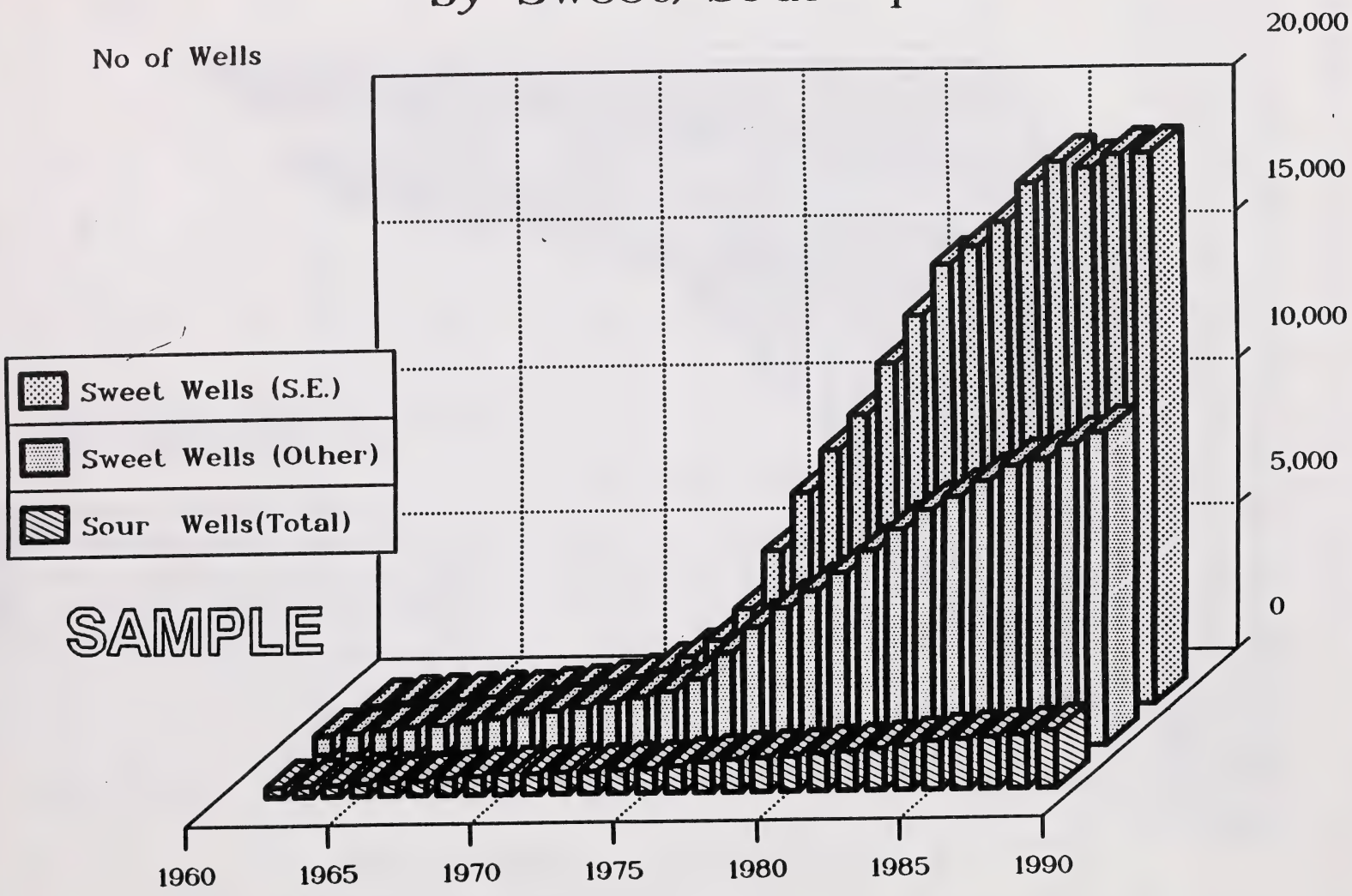


FIGURE 3.2

VOLUMES OF GAS PRODUCED BY SWEET/SOUR SPLIT

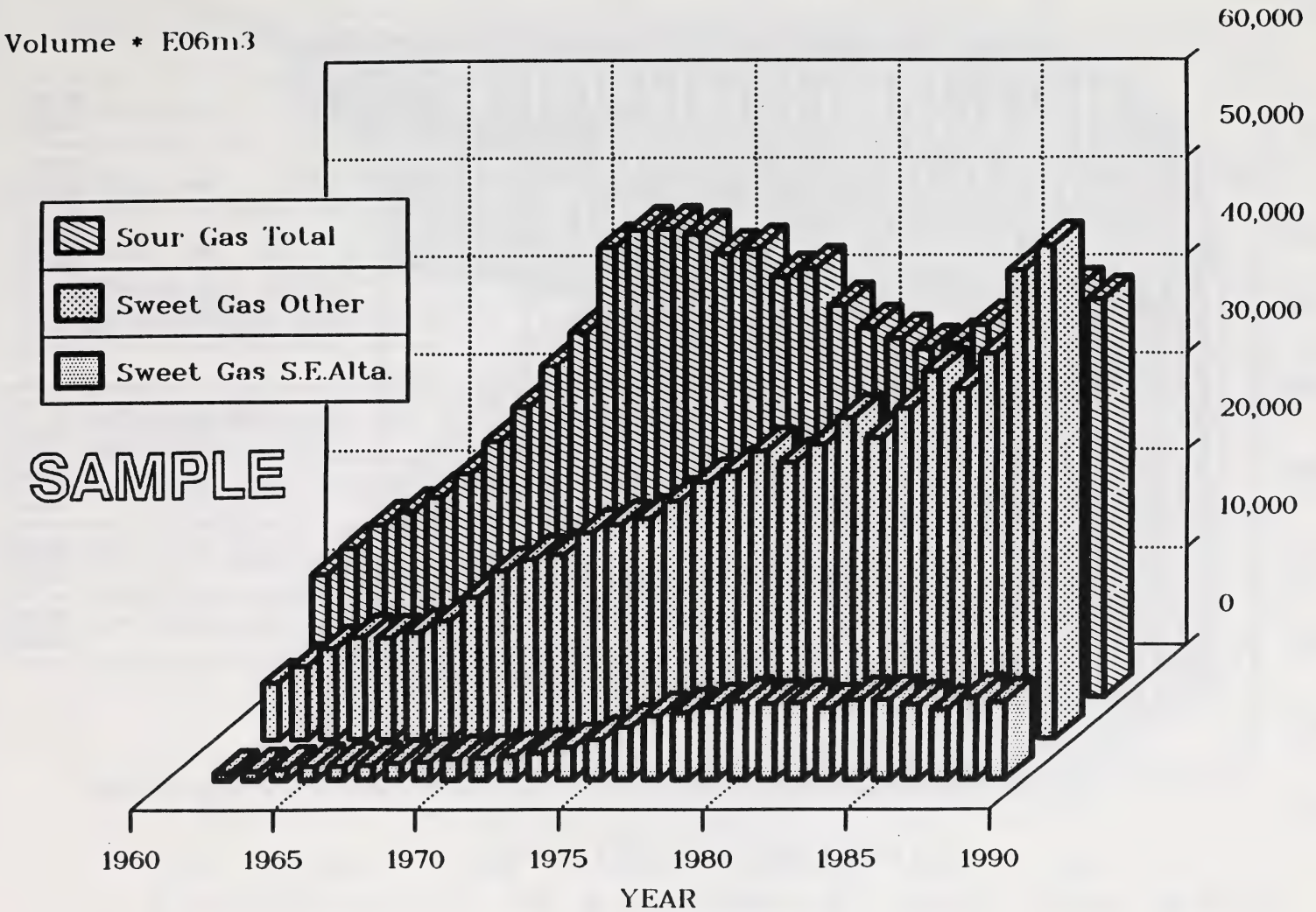


FIGURE 3.3

VOLWELL

Distribution of Producing Sour Gas Wells by H2S Content

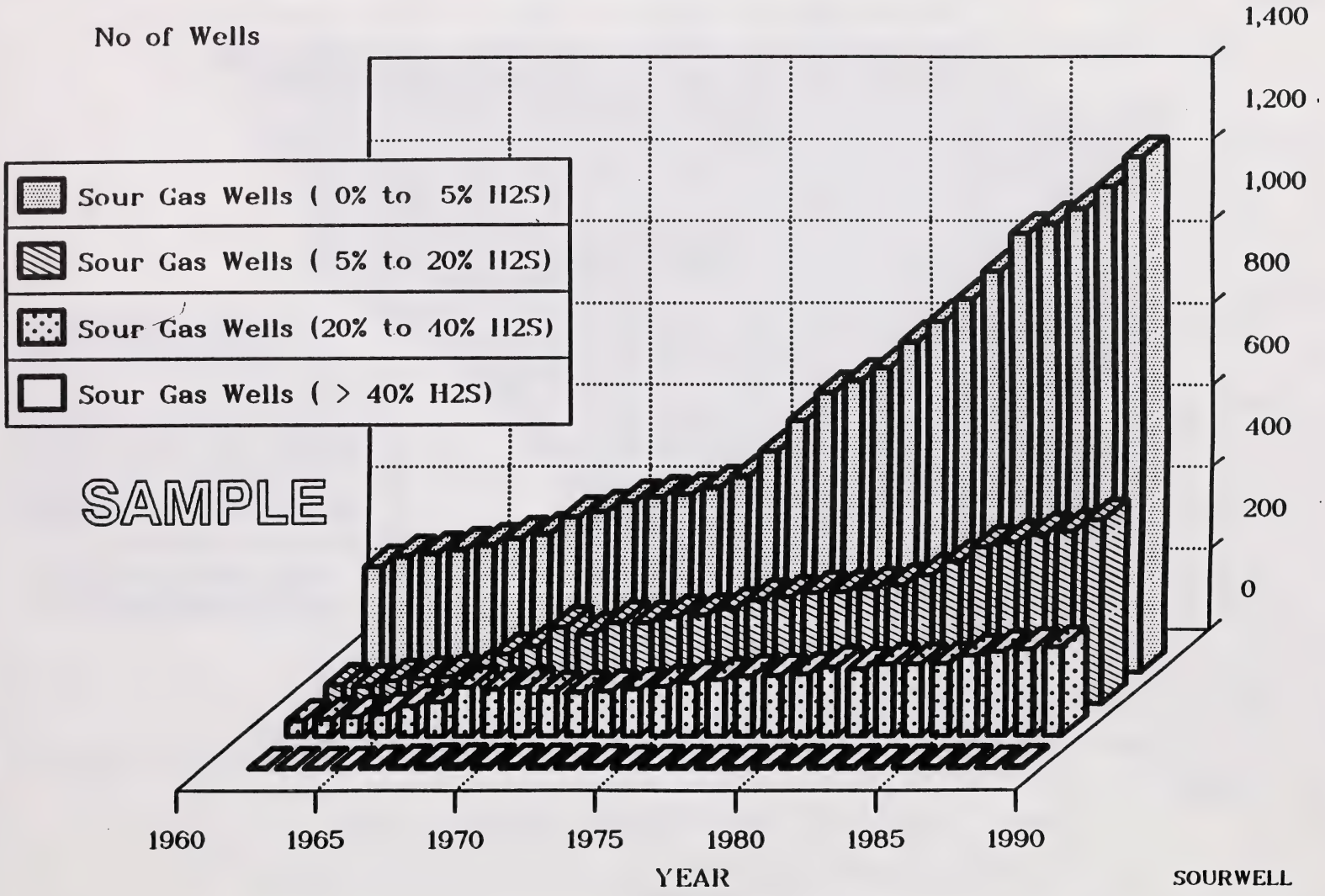


FIGURE 3.4

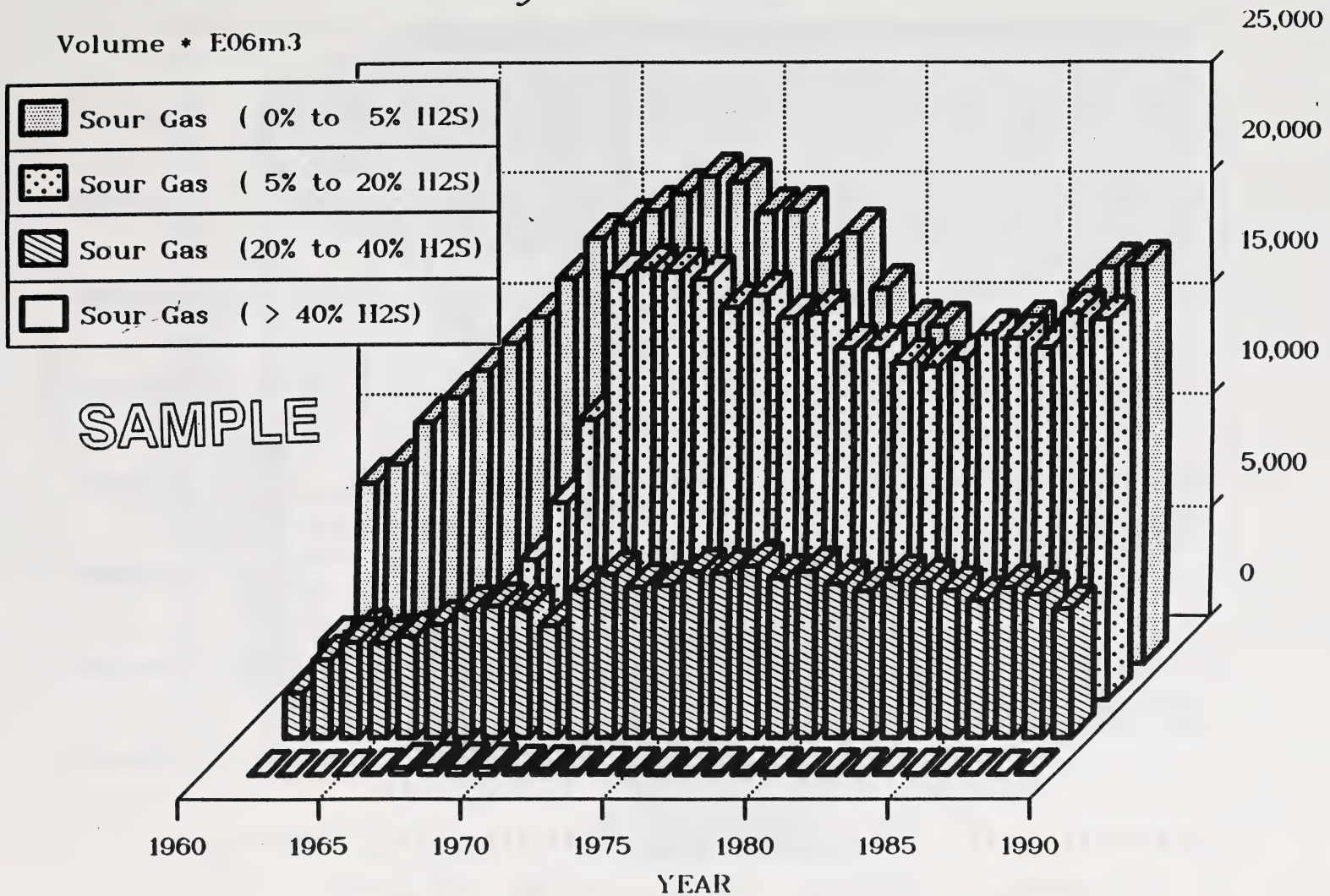

Distribution of Sour Gas Volumes
by H2S Content
Volume * E06m3
Sour Gas (0% to 5% H2S)
Sour Gas (5% to 20% H2S)
Sour Gas (20% to 40% H2S)
Sour Gas (> 40% H2S)
SAMPLE
25,000
20,000
15,000
10,000
5,000
0
1960
1965
1970
1975
1980
1985
1990
YEAR

FIGURE 3.5

TOTAL SULPHUR PRODUCTION From Producing GAS WELLS in Alberta by Well H2S Composition

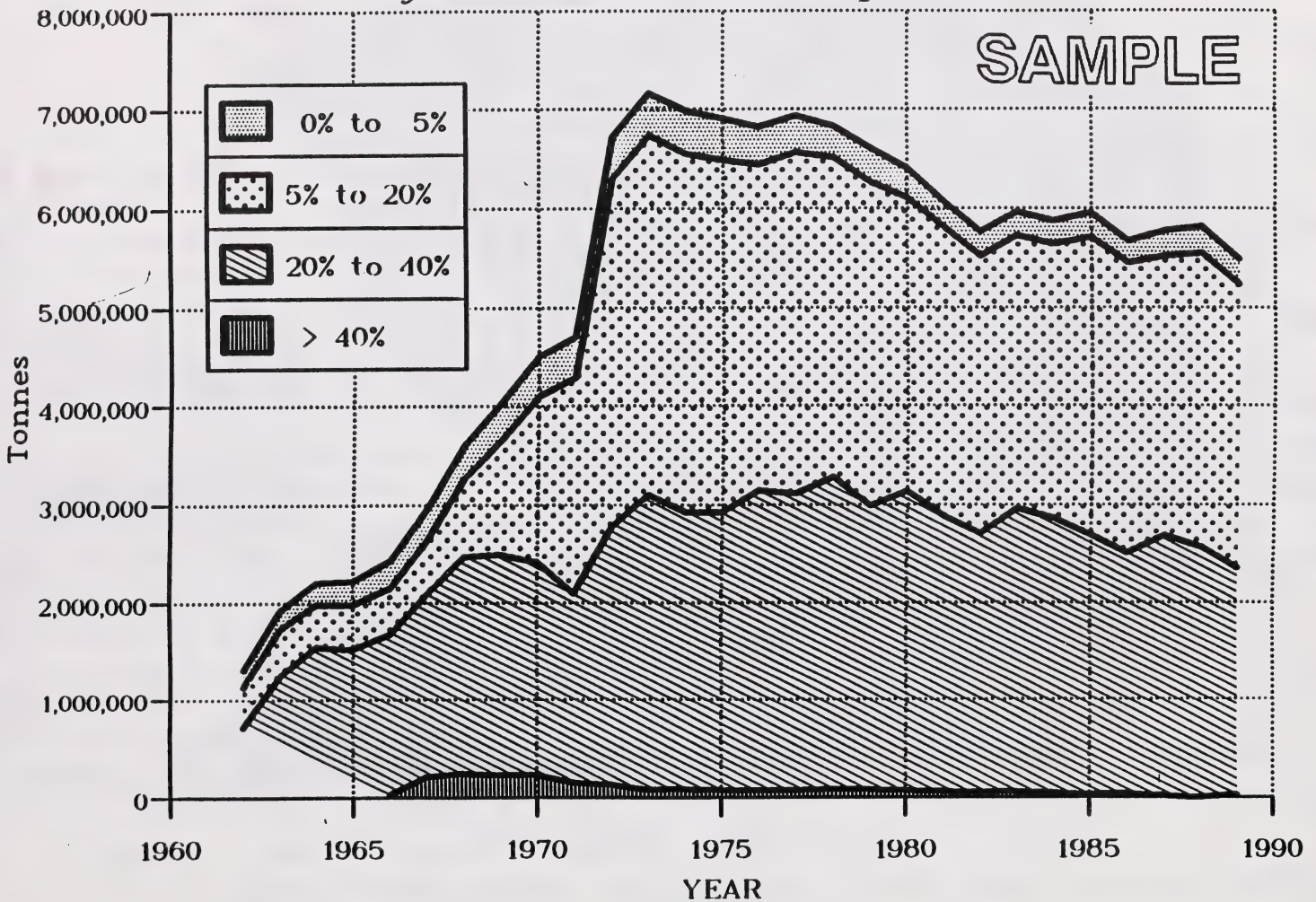


FIGURE 3.6

SULPLINE

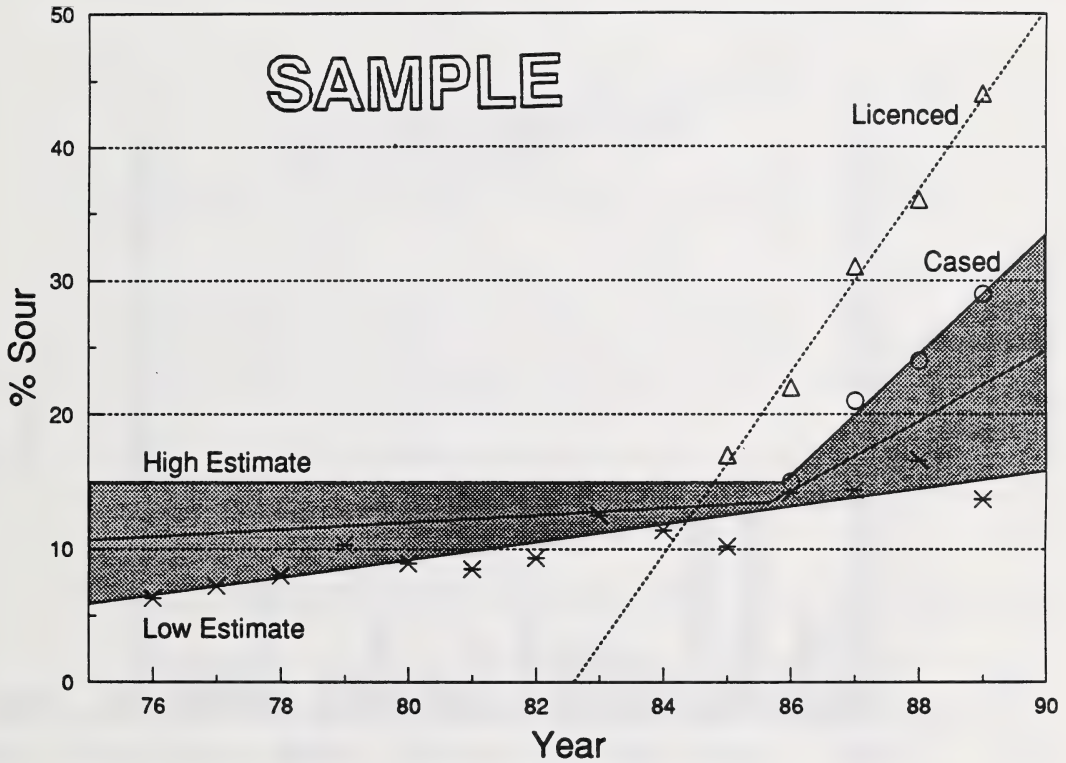


Figure 3.7

Estimates Of Percentage Of Sour Wells Drilled Between 1976 And 1989

Triangle data from Table 3.23
Circle data from Table 3.22
Star data from Table 3.21

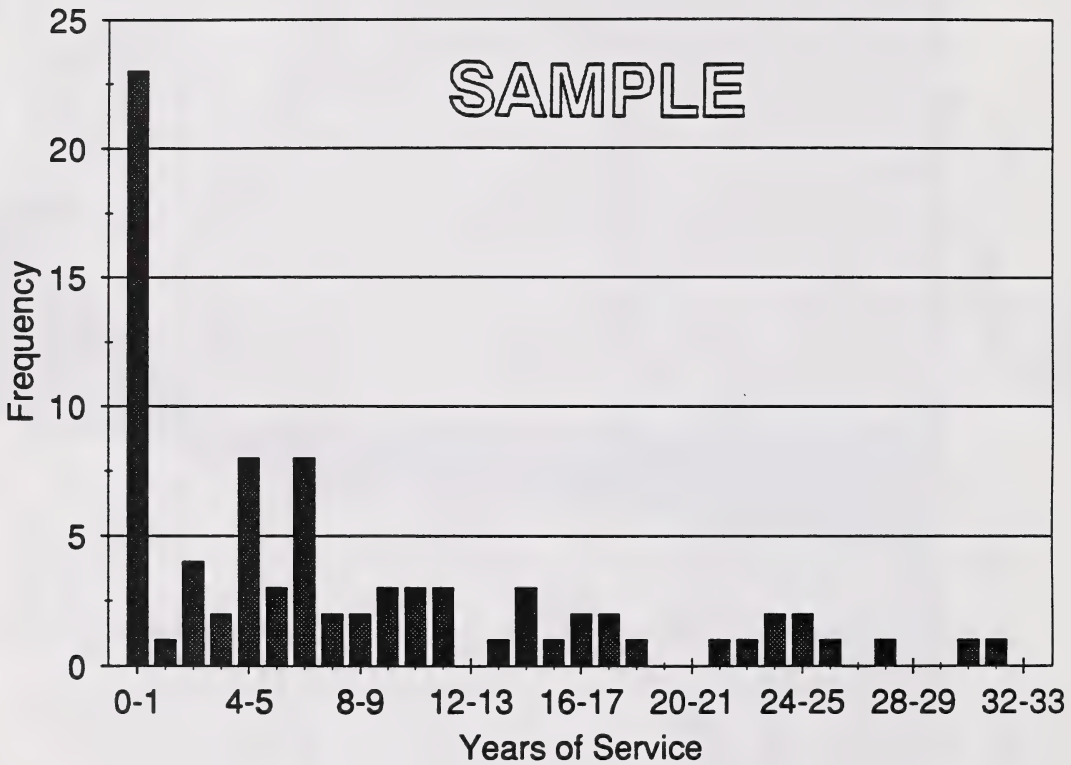


Figure 4.1

Frequency Distribution Of Well Blowouts By Age Of Well.

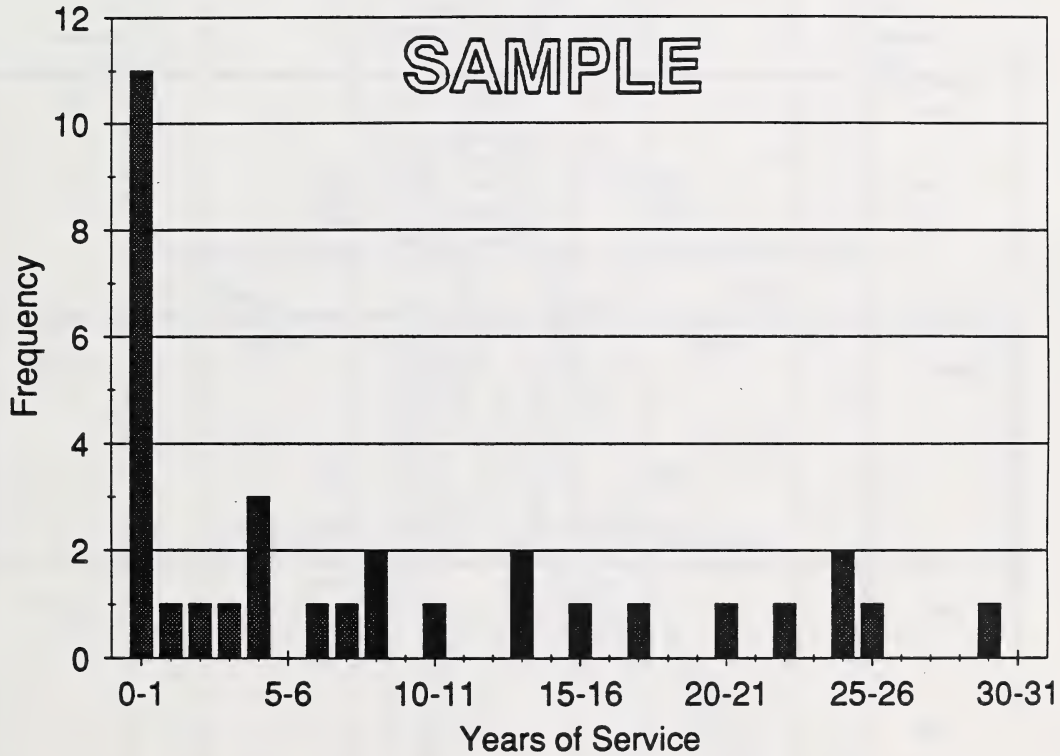


Figure 5.1

Frequency Distribution Of Pipeline Ruptures By Age Of Pipeline.

FIGURE B-1

TOXIC LOAD - HYDROGEN SULPHIDE

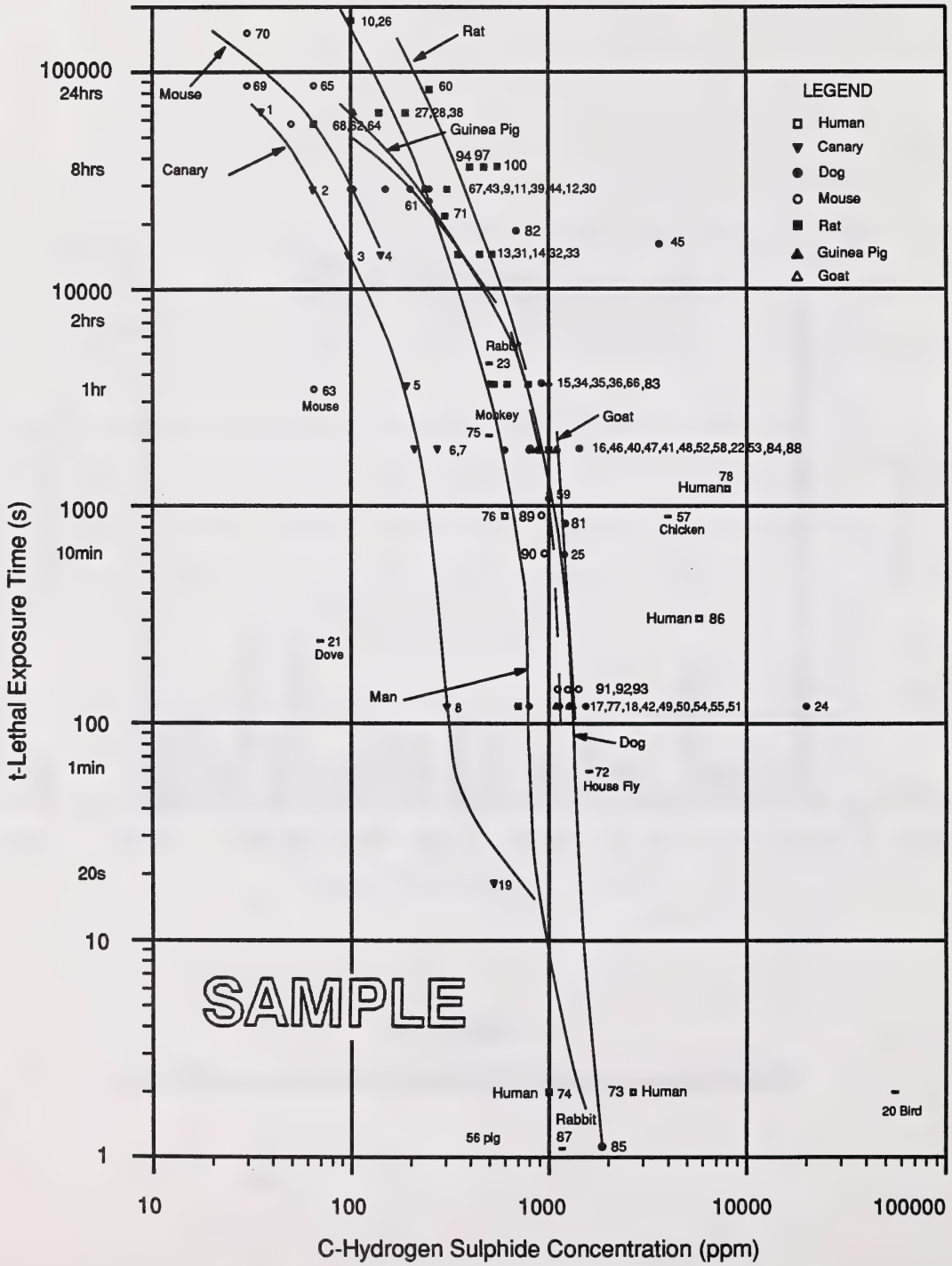


FIGURE B-2

TOXIC LOAD - HYDROGEN SULPHIDE

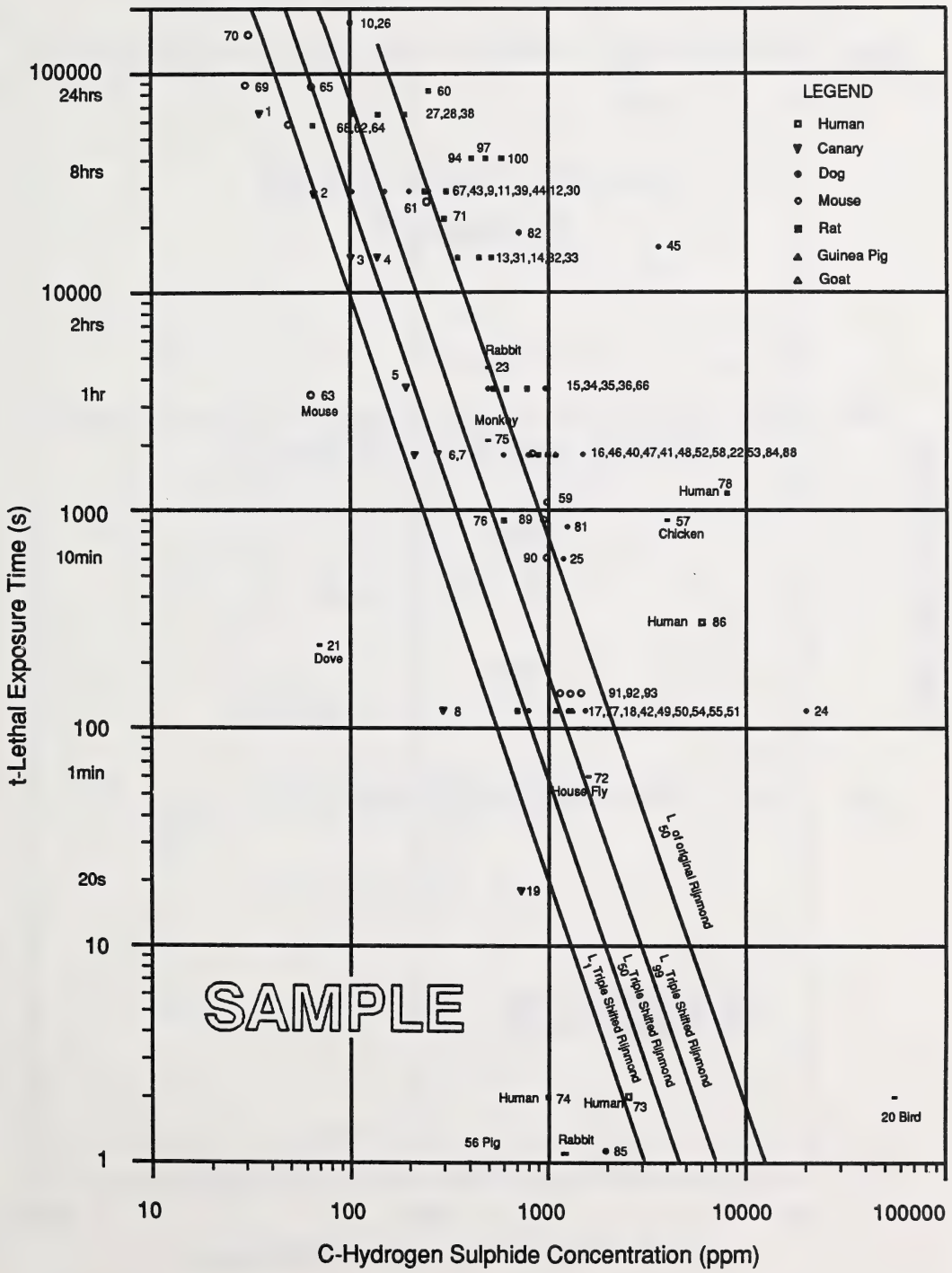
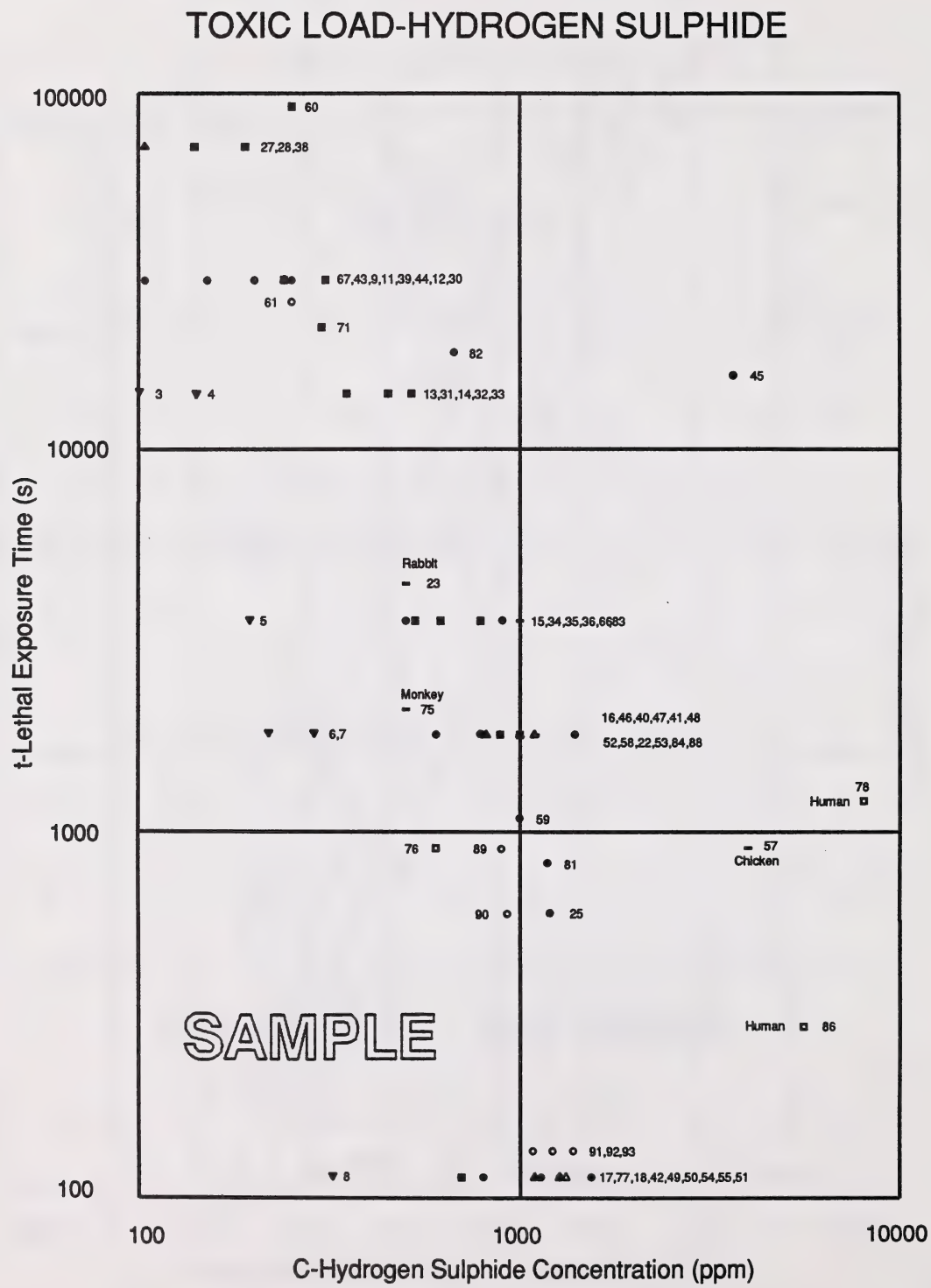


FIGURE B-3


TOXIC LOAD-HYDROGEN SULPHIDE
100000
10000
1000
100
t-Lethal Exposure Time (s)
100
1000
10000
C-Hydrogen Sulphide Concentration (ppm)
60
27,28,38
67,43,9,11,39,44,12,30
61
71
82
45
3
4
13,31,14,32,33
Rabbit
23
5
15,34,35,36,6683
Monkey
75
16,46,40,47,41,48
6,7
52,58,22,53,84,88
78
Human
59
76
89
57
Chicken
81
90
25
SAMPLE
Human
86
91,92,93
8
17,77,18,42,49,50,54,55,51

ERCB and Concord
Volume 8

GASCON2 User Guide

NOT INCLUDED IN SUMMARY

SAB
Volume 9

Scientific Advisory Board Commentary on Technical Aspects of Volumes 4, 5 and 6

NOT INCLUDED IN SUMMARY

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3 3286 10250659 5